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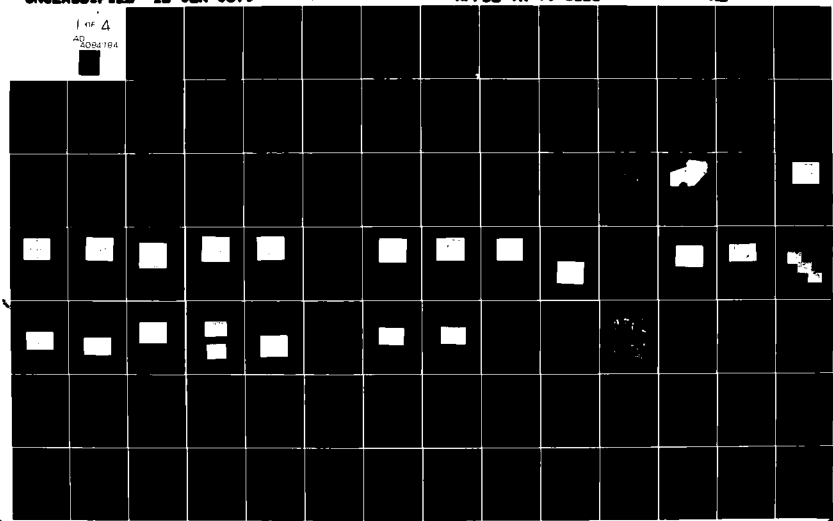

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LEVEL II

FEASIBILITY STUDY FOR INTEGRATED FLIGHT TRAJECTORY CONTROL (FIGHTER)

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INSTRUMENT DIVISION
LEAR SIEGLER, INC.
GRAND RAPIDS, MICHIGAN

NOVEMBER 1979

TECHNICAL REPORT AFFDL-TR-79-3123
Final Report for Period June 1977 – June 1979

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William L Young Jr

WILLIAM L. YOUNG, Jr
Project Engineer
Control Systems Development Branch
Flight Control Division

Evard H Flinn

EVARD H. FLINN, Chief
Control Systems Development Branch
Flight Control Division

FOR THE COMMANDER

M. A. Ostgaard

MORRIS A. OSTGAARD
Acting Chief
Flight Control Division

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number):

The proliferation of increasingly sophisticated enemy military forces in the past decade, and the ability to quickly apply those forces anywhere in the world, has stressed the importance of a demonstrated deterrent capability. This capability should combine rapid reaction with the ability to apply the appropriate force at the appropriate place. Strategic and tactical power, global mobility and precise, well-ordered strike capability are necessary parts of the required capability. (continued)

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20. Abstract (continued)

Communication and accurate time-space coordination will be required capabilities. The ability to strike at night and in adverse weather and to successfully redirect to a higher priority target, all in a well-coordinated manner, will help to offset the superiority of enemy aircraft numbers.

The Integrated Flight Trajectory Control (IFTC) program has been concerned with solving these problems. The solution involves the development of a system which adds flight management capabilities through the use of digital computers to integrate guidance and control with control and display, navigation, weapon delivery, data-link systems and other on-board sensors.

On-board, realtime trajectory generation was developed as a vital part of the total solution. This trajectory generator operates in four dimensions, X, Y, Z and time, with time being specified as critical times-of-arrival at key mission points.

The trajectory generator responds automatically to pilot inputs, data-link inputs or computer-generated stimuli such as would occur when it was detected that the nominal flight profile violates a SAM kill envelope.

Following system development, the concept was demonstrated by realtime, man-in-the-loop simulation in the LSI Hybrid Computing Facility.

FOREWORD

The research reported herein was accomplished for the United States Air Force by Lear Siegler, Inc., Instrument Division, under Contract F33615-77-C-3025, Work Unit 24030229. The Air Force Flight Dynamics Laboratory, Wright-Patterson Air Force Base, sponsored the program.

Mr. William L. Young of AFFDL/FGL was the Air Force Project Engineer and Mr. Greg Comegys was the Principal Investigator for Lear Siegler, Inc. The research and demonstration was performed during the period from February 1977 to November 1979.

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FEASIBILITY STUDY

FOR

INTEGRATED FLIGHT TRAJECTORY

CONTROL (FIGHTER)

1 INTRODUCTION AND SUMMARY

1.1 INTRODUCTION

The proliferation of increasingly sophisticated enemy military forces in the past decade, and the ability to quickly apply those forces anywhere in the world has stressed the importance of a demonstrated deterrent capability. This capability should combine rapid reaction with the ability to apply the appropriate force at the appropriate place. Strategic and tactical power, global mobility, and a precise, well-ordered strike capability are necessary parts of the required capability.

The next major confrontation will likely be intense, tactical, and non-nuclear, at least during the initial phases. The battle area will be defended heavily by defensive weapons (SAMs, AAA) and enemy fighter aircraft. The number of enemy fighters will probably exceed the number of friendly aircraft. The friendly pilot will be concerned with enemy aircraft and ground defenses. Therefore, by giving the pilot an accurate, current knowledge of his tactical situation, his probabilities of survival and mission success are increased.

Communication and accurate time-space coordination will also be required capabilities in the next conflict. The ability to strike at night and in adverse weather, and to successfully redirect to targets of a higher priority -- all in a timely and well-coordinated fashion -- will help to offset the superiority of enemy aircraft numbers.

The increases in more sophisticated weapons, on-board sensors, and aircraft and control freedom will be accompanied by increases in pilot workload. Unless the control tasks are automated and simplified to reduce the pilot's workload, the cockpit workload will become an unmanageable effort.

The Integrated Flight Trajectory Control (IFTC) program has been concerned with solving these problems. The solution is not simply one of a better design of the cockpit controls and displays which reduces the number of button pushings and switch selections. It must involve the development of a system which adds flight management capabilities through the use of digital computers to integrate guidance and control with control and display, navigation, weapon delivery, data link systems, and other on-board sensors.

The IFTC program objective was to expand the flight management capabilities of on-board equipment to reduce the pilot workload required to operate in a hostile tactical environment including real-time mission redirects provided by data links or pilot initiative.

The projected tactical scenario characterized by superior numbers of enemy air and ground offensive and defensive systems will require the friendly forces to maintain tactical air superiority through efficient use of their aircraft; in other words, through the use of force multipliers. Friendly forces will fly missions into enemy territory under night and adverse weather conditions to neutralize enemy ground movements. Because of the fluid nature of the battle area, command and control (C^2) will be heavily utilized for directing and redirecting airborne forces. Jam-resistant digital communication links will supply C^2 directives and up-to-date ground and airborne threat information. Command and control systems such as the Joint Tactical Information Distribution System (JTIDS) will receive timely information from such sources as Quick Strike Reconnaissance (QSR) aircraft, Precision Emitter Locator Strike System (PELSS), Airborne Warning and Control

System (AWACS), and from other JTIDS-user aircraft. Precision navigation information for night and adverse weather operation will be available through such sources as the Global Positioning System (GPS) and the JTIDS relative navigation capability.

Many of the mission types will be characterized by complex profiles with one or more time-critical points such as time-on-target (TOT), time at the FEBA crossing for IFF, and time-of-arrival at the refueling tanker. Specific types of missions which would be enhanced by precision time-space coordination are:

- Air assault missions requiring timely support from air defense, stand-off jammers, and gunships for mission success and survivability.

- Interdiction missions requiring time scheduling of the suppression of enemy defenses.

- Airlift missions requiring timely air and ground defense support during time intervals of high vulnerability to enemy attack.

- Night and adverse weather missions flown in conditions with high cockpit workload.

The possibility of a redirect occurring during any of these mission types is high. The real-time redirection capability and the increased availability of tactical data provided by the data-link network should serve as a force multiplier for the friendly forces. This capability, however, will undoubtedly increase the cockpit workload. Targets will change, refueling will be rescheduled, ingress/egress routes will vary, and deviations because of hostile bogies, SAM, and AAA threats will occur.

With existing cockpit capabilities and a redirect based on the JTIDS position messages the new mission routes would be plotted on the navigation maps. Aircraft performance charts would be used to determine fuel usage based on rough-cut time-of-arrival and airspeed calculations. Rendezvous for refuel and bingo fuel points would be considered. Survivability would be a prime consideration. The total threat situation would be assessed with respect to the new mission profile.

If the redirected mission is of sufficient priority to warrant the risks, the pilot must indicate to his controller the decision to comply and enter the appropriate data into his navigation equipment. If the pilot determines that he cannot comply, the entire process repeats, and a prime target may escape destruction.

These plan variations can and will occur after takeoff, and the pilot's ability to respond favorably to each will be determined by the implementation of the cockpit controls, displays, and sensors.

Existing cockpit equipment (autopilots, flight directors, and inertial navigation systems) provide pilot relief and steering cues for flying under essentially constant conditions of attitude, heading, altitude and speed, or for flying straight line segments between stored mission destination points. This equipment, with navigation maps and hand calculations, are used to navigate the mission route and meet any specified target and rendezvous times. Fuel-remaining estimates at mission and refuel points are computed during the mission planning exercise. Deviations from this original mission plan, caused by the need to avoid the lethal airspace around a new enemy SAM location, by the need to divert from the current course because of the proximity of hostile bogies, or by profile changes to take advantage of terrain features for radar masking, will require the pilot to work with the navigation maps to determine the best return path to the original mission profile. These disruptions, of course, will force the revisions of the profile, the time schedule, and the fuel use estimates.

This level of cockpit workload is formidable under non-combat circumstances, and nearly impossible under the stress associated with combat situations. Furthermore, planning for mission changes and redirects reduces the time available for operation of radar, communication receivers, navigation equipment, and jamming equipment. Heads-up "window time" necessary for early visual detection of enemy aircraft, a major concern and activity, is also greatly reduced.

To restate the concern of the IFTC program: Given a dense threat environment, a fluid battle situation, the availability of large amounts of tactical information, and in a redirect posture, the potential for increased pilot workload will in all likelihood make the pilot the limiting factor in the execution of time-critical and redirected missions. Consequently, the operational improvements provided by C^2 and other advanced tactical systems may not be achieved reliably because of the inability of the pilot to assimilate the tactical situation information and translate the effects of that information into appropriate aircraft control actions.

The following pages summarize the work performed by the Lear Siegler Instrument Division, Grand Rapids, Michigan, on the Integrated Flight Trajectory Control concept, under sponsorship of the Air Force Flight Dynamics Laboratory, Flight Controls Division, Wright-Patterson Air Force Base, Ohio.

1.2 IFTC PROGRAM HISTORY

The IFTC tactical fighter program was an extension of an earlier study that applied the concept of automatic, on-board four-dimensional trajectory generation and automatic guidance and control along the trajectory to the terminal area control requirements of military transports [1, 8]. Included in the final report for that program were recommendations for further study. The major elements of the recommended program were to:

- Apply the concept to fighter aircraft mission tasks such as weapon delivery and rendezvous. Refine the trajectory algorithms and control/display system and demonstrate performance with a fighter simulation.

- Demonstrate, on the simulator, the operational improvements achievable with a data link (JTIDS-like)/IFTC integration.

- Define and implement a vertical situation presentation for the Tactical Situation Display in the cockpit simulator. (The transport study identified the need for the vertical situation mode.)

- Develop, simulate, and evaluate an optimal control technique for the IFTC control law. Determine if the optimal control technology provides significant tracking performance improvements over a classically designed control law and if an optimal control algorithm is realizable in an airborne computer.

The first three recommendations were included in the current IFTC tactical fighter program. The fourth recommendation has been embodied under another Flight Dynamics Laboratory contract, the Flight Trajectory Control Investigation program.

After review of representative tactical fighter missions -- both current and anticipated -- four major areas were identified as requiring refinement of the algorithms developed for the transport program. In addition, a blind mode weapon delivery capability was added.

- Four-dimensional trajectory generation
- Flight control laws
- Man/machine interface
- Automatic data link interaction (JTIDS-like)
- Blind mode weapon delivery

In particular, the algorithms were modified to provide increased capability for the following tactical situations:

- Rendezvous with moving waypoints
- Display of vertical trajectory information
- Perform weapon delivery with IFTC control to the identification point (IP)
- Track-up mode on the tactical situation display (TSD)
- Automatic threat avoidance under IFTC control
- Ability to respond to mission redirects

Following the modification phase, the algorithms were programmed in FORTRAN and installed in the Lear Siegler, Instrument Division Hybrid Computing Facility. Following the checkout period, the simulation was used for performing real-time, man-in-the-loop system analysis and verification, pilot testing, and concept demonstrations. The contract was awarded 02 May 77 and concluded on 02 June 79.

1.3 SUMMARY

The next nine sections of the report describe the results of the program activities. A brief summary of those activities is offered here.

Section 2 contains the system description and a discussion of the operational capabilities. The relationships among the navigation, communication, aircraft flight controls, and cockpit displays and controls are described. The trajectory generator computes a four-dimensional trajectory based on data defining the mission profile and known threats. For critical mission points the pilot may specify times-of-arrival and ground speeds. These are used as hard constraints by the trajectory generator when computing the 4-D profile.

As a result of having a completely defined 4-D profile, it is possible to compute fuel use estimates and arrival time windows for each point and segment of the flight plan. In addition, the nominal profile is adjusted to avoid the lethal airspace of known ground threat emplacements. The aircraft performance capabilities and the control law authority limits serve as constraints for the computed trajectory, to assure flyability.

Guidance and control functions provide commands for profile tracking and maintaining the speed and time schedule. Both automatic and manual control modes are selectable. In automatic mode control, signals are output to the simulated servo systems for the ailerons, elevators, and throttles. In the manual mode, pitch, roll, and throttle command cues for pilot tracking are provided on the ADI.

The control and display design goal philosophy was to minimize the number of pilot actions required to communicate with the IFTC system. The pilot is always regarded as the final decision maker, however, and the displays were designed to allow the pilot to make a quick assessment of the changing tactical environment to aid that decision-making process. Electronic displays, keyboards, and extensive computer automation were used to accomplish that goal.

Data-link information is processed automatically by the computer and presented on the displays. Such data-linked events as mission redirects, hostile and friendly bogies, and new ground threats were demonstrated by the simulation. The trajectory generator is fully interactive with the data-link inputs, providing "capture" profile generation during evasive maneuvers and modified trajectory segments to avoid ground threat envelopes.

The operational capabilities, Section 2.2, outlines the expected uses and benefits of the IFTC system in a volatile tactical environment. Workload relief is also discussed. Operational capabilities in a centrally coordinated environment as well as autonomous operations are considered.

The goal of the program was to develop and demonstrate advanced, mission-oriented, highly-integrated system concepts which will permit the crew to function in a higher level, mission management role, compatible with the tactical environment and the advanced sensors and communications systems presently under development. Following the development, programming, and checkout phases of the program, the objective was to demonstrate the concept in the simulator. For this purpose a typical penetration, air-to-ground weapon delivery mission was constructed in concert with Air Force tactical pilots.

A typical demonstration briefing for Air Force personnel consisted of the following activities:

- Overhead viewgraph briefing on the program history and objectives - LSI personnel.
- Briefing on the compatibility and coordination of the IFTC program with other Flight Dynamics Laboratory programs - Air Force personnel.
- 35-mm slide briefing with a step-by-step discussion of the mission events - emphasizing the benefits afforded by the IFTC concept for each phase of the mission - LSI personnel.
- Execution of the mission in the simulator - flown by LSI personnel.
- Simulator flight by Air Force personnel, when requested.
- Debriefing between LSI and Air Force personnel.

The details of the demonstration mission are given in Section 3. Approximately 12 briefings and demonstrations were given to Air Force personnel between 11 October 1978 and 22 May 1979. During this same time period, an Air Force 16-mm color and sound movie was produced[5], describing the concept and showing the simulator displays during typical mission events.

Section 4 describes the results of the pilot testing conducted during February, 1979. Three subject pilots were used. Each pilot spent a day and a half being briefed and trained; this included about 3-4 hours of simulator time. The demonstration profile was used for pilot training and a different, lengthier profile was used for the testing. The pilot testing was designed to answer several questions such as:

- What did you use to judge the performance of the system?

- Does the IFTC capability assist the pilot by making higher level decision-making information available to him?

- Does it increase his ability to respond to a changing tactical environment, C^2 redirects, and targets of opportunity?

- Does it increase his probability of mission success and survivability?

- How should the information be displayed to the pilot?

- Can the capability be utilized to decrease his preflight planning requirements?

The self-formulated criteria used by the pilots to judge the performance of the system was the ease or lack of ease with which the pilot could interact with the system, and whether or not it aided his ability to avoid threats, accept redirects, and hit targets.

In response to the question, "What operational needs do you think a trajectory generator will satisy?", the pilots responded:

> "Should greatly improve a single-seat pilot's ability to accurately navigate to the target and absorb data-link inputs."

> "Allows (with TSD) estimates of track crossing points and anticipation of intercept points; also to determine intent of hostile aircraft."

> "Ability to reach target after A/A or A/G threat has gotten pilot off course; ability to react to a redirect."

Threat display and avoidance was considered beneficial because survival potential was felt to increase directly with situation awareness, and because of the feeling that available intelligence information just wouldn't be accurate enough.

Generally, the pilots felt that a cockpit filled with the systems projected for the future would be unmanageable without the systems integration help afforded by an IFTC-like system, particularly for the single-seat cockpit. The consensus was that IFTC should result in greatly increased capability without a corresponding increase in workload.

All pilots felt that the Tactical Situation Display (TSD) is not only useful, but a necessity as are the flight director commands on the ADI and the advisory commands on the airspeed and altimeter displays. The vertical display mode of the TSD was considered useful at the start of ascent/descent points and for visualizing those short flight legs with relatively large altitude changes.

As would be expected, all pilots considered a HUD to be necessary. Pilot recommendations included revising the format on some status display pages and providing easier access (less button pushing) to certain classes of information. More specifically, the recommendation was to provide estimated times-on-target and fuel reserves at refuel points on the TSD, especially when a redirect is requested. This would provide the pilot with instant access to this information and would expedite his comply/not comply decision-making process.

Also recommended was the implementation of a moving map display in place of the TSD. This moving map display would provide electronic map generation overlaid on the projected image of a geographic map. The obvious advantage of this combination is the better reference of the electronic map and related symbology to the real world. Redirects and recoveries from diversions would be viewed in relation to other geographic landmarks and terrain features. In many cases, the pilot could tailor his own flight profile using the onboard control and displays to take advantage of these terrain features.

It was also suggested that a heads-up display (HUD) be installed in the simulator cockpit. This would allow an investigation of the types of information to be displayed on the ADI, TSD, and HUD, which data should be redundant, and which data should be switched among the displays as a function of the mission phase. The HUD would also permit a better evaluation of the usefulness of the TSD when flying in a heads-up rather than a heads-down posture.

Section 5 is a description of the four-dimensional trajectory generator. This section begins with a discussion of the parameters used to define a navigation point and specifies which are required and which are optional. The horizontal path discussion describes the linking of horizontal profile segments of all the points defining the mission. The basic building blocks for the horizontal path construction, "curved-straight" and "curved-straight-curved", are discussed in detail.

Next discussed are the techniques for constructing the vertical aspects of the trajectory as a function of the vertical parameters assigned to each waypoint. The horizontal and vertical segments define a three-dimensional profile. The fourth dimension is added by the speed/time processor which uses the assigned times-of-arrival and speeds and constructs the speed and time schedule for the total mission. This four-dimensional trajectory is used by the guidance functions as the reference or desired trajectory.

In addition to these functions, the trajectory generator includes a threat avoidance algorithm. Under the assumptions that the threat position, and some estimate of the threat type is available, the avoidance algorithm compares the nominal flight profile segments with the threat lethal envelopes and searches for an intersection. When an intersection is detected, the horizontal profile is modified to avoid the threat envelope, and the speed/time aspects of the total profile are recomputed to determine the effects of the flight plan deviation on the time schedule.

Section 6 describes the guidance and control functions. The guidance and flight control laws allow automatic or flight director cued, manual control of the aircraft along the reference trajectory for all phases of the mission, including weapon delivery. The first parts of Section 6 discuss the techniques used for determining the instantaneous reference parameters with respect to the desired profile. These parameters include X, Y position, acceleration, time, velocity, flight path angle, and altitude. The guidance section describes the determination of the horizontal, vertical, and longitudinal errors between the reference state and the actual aircraft position. Also discussed are some techniques used to compute crossfeed terms to minimize altitude loss and speed fluctuations caused by aircraft pitch attitude changes during turns.

Open-loop control terms were added to minimize the introduction of transients into the control feedback loops caused by step changes in the reference bank angle when transitioning from a straight flight segment to a curved flight segment. Throttle activity is also discussed. To minimize excessive throttle activity, a technique was developed to compute a nominal throttle position to provide the needed thrust to offset the predicted drag at a new airspeed. The longitudinal feedback controls were then allowed to make long-term throttle corrections for any throttle position errors.

Also discussed in Section 6 are the control laws used for computing the roll, pitch, and throttle commands used as inputs to the control servos, and the modifications to those same commands to be used as command cues on the ADI flight director system.

The final paragraph of Section 6 discusses the four error criteria used for setting the trajectory redraw flag. The setting of this software control flag is recognized by the trajectory generator which then computes a "capture" trajectory from the current aircraft position to the next point in the flight plan. This curved trajectory represents the most direct path to the next point in the flight plan, and frees the pilot from the often difficult task of navigating back to the original flight plan, following an unplanned mission deviation.

Section 7 describes the control and display aspects of the program. This section consists of four parts:

Control/display integration

Control/display description

Pilot operations

Control/display design philosophy

The man/machine interface was designed with the tactical fighter mission requirements serving as the driving force. The philosophy was to allow the pilot to be placed in the role of a cockpit manager, freeing him to perform visual search for hostile bogies and SAMS, manage the aircraft sensors using the cockpit control heads, and modify his mission as unplanned events occur. The control and displays were identified, designed, and located in the cockpit to provide the pilot with enough information to assess rapidly his fluid tactical environment and make correct decisions based on that assessment.

The major elements of the control/display system which were identified and implemented for the IFTC simulation demonstration were:

- Automatic/manual three-axis aircraft control system
- Cathode ray tube (CRT) displays for pilot interaction with the IFTC system
- Keyboard and flight/display mode controllers
- X-hair designator for rapid system inputs

The control and display implementation for the IFTC fighter demonstration program was built on the knowledge gained in the transport program. Electronic displays provide attitude information and roll, pitch, and throttle command cues; horizontal and vertical situation information; and computer-based alphanumeric information. The concept of computer/pilot interaction was developed to a higher level in the fighter demonstration study by providing mission-oriented mode controls and increased man/machine interaction capability for mission and data management.

The control and display system was installed in the fixed-base simulator cockpit. The main features are:

- Designed for one-man operation.

- Considers the information requirements of the IFTC system and advanced command and control (C^2) operation.

- Provides mission-oriented mode selection.

- Extends the use of the interactive control/display software and hardware design to minimize the pilot's information management task.

- Explores the use of the trajectory generator outputs as a means of providing the pilot with a higher level of decision-making information than is possible without a four-dimensional trajectory generator.

Out of the complexity of the data handling and display problem, and a strong desire to have the control and display design lend itself to a straightforward procedure for implementation and making changes, the theory of finite state machines was used. This technique is described in the last paragraphs of Section 7.

An additional requirement of the fighter demonstration study was the integration of digital data link command and control and tactical situation information with the IFTC system. Data-linked information consisting of waypoint, threat, or target locations and desired TOTs is accepted as inputs by the IFTC system. Trajectories are generated based on the command and control requirements and aircraft and control law constraints and displayed to the pilot on the tactical situation display. Specific numerical data is available to the pilot by using the status display. With the IFTC system the pilot has the advantage of being able to review the data-linked information as an integrated whole in the same display format as his preplanned mission information. Furthermore, as an additional confidence factor, the pilot knows that the IFTC system, and in particular the four-dimensional trajectory generator, has considered speed, fuel, maneuverability and stored tactical information such as known SAM emplacements when the command and control information was processed. For the IFTC demonstration program, the following classes of command and control information and directives were included:

- Mission redirects
- Target of opportunity redirects
- SAM and AAA threat positions
- Hostile and friendly aircraft locations

The data link simulation is discussed in detail in Section 8.

Section 9 describes the simulator and facilities used for the IFTC simulation. Three digital computers, a hybrid (analog-digital) and an analog computer were used. In addition to the computers, a single-seat, F-16-like cockpit with instruments and interfacing electronics was used. An F-4D aircraft model was implemented, and all processing, including the trajectory generation, guidance and control, and control and display functions, occurs in real-time which made possible man-in-the-loop demonstration and testing.

Section 10 describes the weapon delivery implementation. The blind mode weapon delivery algorithms from the Air Force ARN-101 Digital Modular Avionics System (DMAS) were implemented for the IFTC demonstration program. If automatic flight control is selected during weapon delivery, only the roll axis is coupled, freeing the pilot to manually fly the pitch axis. Three options are available for pitch axis control: (1) follow the pitch steering cue which will put the aircraft into a shallow dive and results in weapon release just prior to reaching the break altitude; (2) continue flying at essentially constant altitude until weapon release; (3) when in-range, perform a pull-up maneuver, with approximately 4 g's as the limit. In all cases steering to the release point and release time computations are performed automatically. If the Blind mode is engaged and the pickle switch is depressed, automatic weapon release will occur.

The flight control law allows automatic or flight director-cued manual control of the aircraft to the identification point (IP) prior to performing the weapon delivery mission. At the IP the IFTC steering smoothly passes control of the aircraft to the weapon delivery steering and release time prediction algorithms. Weapon delivery steering maintains control of the aircraft to the computed weapon release point, and then returns control to the IFTC system for automatic or cued manual control to the egress point.

Also discussed in Section 10 are the bomb ballistics integration technique and the drag model for the Mark 82.

1.4 RECOMMENDATIONS FOR FUTURE WORK

The Integrated Flight Trajectory Control program has shown by analysis, simulation, demonstration, and testing that the concept of on-board, real-time computation of four-dimensional trajectories in response to inputs from the pilot, inputs from ground and air threat detection sensors, and inputs from advanced digital data links is very possible. The program has demonstrated the ability of the same digital technology to generate guidance and control signals for automatic control of the aircraft along this four-dimensional reference trajectory, thus freeing the pilot to become more of a cockpit manager of his on-board systems and sensors.

The program has also demonstrated the advantages of a well-designed, mission-tailored interactive control and display system in which the computer is an active element of the decision-making process.

These capabilities should increase the survivability and probability of mission success, increase his capability for performing night/all-weather operations, and increase his ability to respond to mission redirects.

An additional output of this program is recommendations for future effort that would further demonstrate or verify the operational benefits of the system. The following recommendations are offered in that spirit:

- Install and implement a projected map display (PMD). This would allow the display of actual geographic map information, combined with electronically generated flight profiles, threat envelopes, and bogey positions. This capability would demonstrate the increase in the pilot's orientation and confidence with respect to the tactical environment, and the elimination or reduction of the use of hand-held maps. With the implementation of an interactive X-hair designator on the map, it would also demonstrate the aiding of the pilot's communication with the avionics computer.

- Incorporate the mission data transfer system (MDTS) into the simulation. This sytem was developed for the AN/ARN-101 Digital Modular Avionics System and consists of a briefing room minicomputer and displays, a data module which is loaded with the mission data in the briefing room, and a receptacle in the cockpit into which is inserted the module for rapid transfer f mission data to the cockpit computer. Having the data transfer system implemented would give pilot-evaluators a "hands-on" demonstration of the total operational capabilities of IFTC in a future aircraft weapon system. Using the currently accepted methods of loading the navigation or mission computer, many evaluators are concerned that because IFTC processes so much data to generate a complex flight plan, that the pilots will be required to spend a great deal of time, prior to takeoff, performing manual data insertion. In fact, with MDTS the IFTC system will significantly decrease the pilot workload both during the planning exercise and the actual data load to the airborne computer.

- Implement advanced air-to-ground weapon delivery equations to replace the conventional weapon delivery currently mechanized. As part of the Firefly program [6], advanced air-to-ground bombing equations have been developed for guiding the aircraft along curvilinear attack paths for automatic weapon release in a non-wings-level attitude.

  Since the IFTC trajectory computation techniques and the Firefly curvilinear weapon delivery techniques are concerned with different portions of the attack problem they are complementary, and the integration of the two techniques offers the potential for increased aircraft survivability over the entire mission profile.

- In addition to implementation of the Firefly weapon delivery techniques, the IFTC simulation could be used to demonstrate the "pop-up" weapon delivery maneuver and its inherent advantage of minimizing the total time of aircraft exposure to ground defenses during the delivery maneuver. Because the simulator is fixed-base and without a visual reference projection system, the actual target acquisition and tracking phases of the maneuver could not be demonstrated; however, the simulator could be used to demonstrate the capability of the trajectory generator to compute a profile to the pull-up point

(P.U.P.), cue the pilot via the HUD or ADI to begin the pull-up maneuver, initiate the roll and pull-down, and roll-out to begin target tracking.

A current Air Force goal[7] is to have the forward area controllers (FACs) standardize their target briefing for a redirect, irrespective of whether they're talking to an A-10, an F-4, or an F-16 pilot (or any other, for that matter). In a highly jammed situation the FACs could burst-transmit four items of information:

a. The pre-designated IP (in code)
b. Heading to the target
c. Distance to the target
d. Type target/target elevation

With considerable variations in airspeed and maneuverability from aircraft to aircraft, this goal places a considerable responsibility on the pilot, but it can be done. To quote from [7]: "However, with only these four pieces of information, the mission can be accomplished. Also, by giving this type of information; i.e., 'distance to target' as opposed to 'time to pop point', the FAC is not dictating tactics to the strike flight. Airspeed, formation, and other tactical considerations are now the responsibility of the iron haulers, and this is as it should be. However, with this type of information, the strike flight has not been spoon-fed anything that tells them how to get to an appropriate pop point. So the next question is, 'How do I get there from here?'"

This question is answered for the pilot by the IFTC system. Knowing the airspeed, current aircraft position, IP position, heading-to-target and range-to-target, the trajectory generator creates a curved-path profile to the IP point which satisfies the flyover heading, and determines where the pull-up point should be with respect to the IP and target. The trajectory is drawn on the TSD to enable the pilot to become quickly oriented to the new situation.

2 THE INTEGRATED FLIGHT TRAJECTORY CONTROL CONCEPT

2.1 SYSTEM DESCRIPTION

The Integrated Flight Trajectory Control program has developed an on-board system concept that will provide pilots with increased flight management capabilities during the execution of tactical missions. The key functions used to accomplish this are:

- Real-time computation of four-dimensional (x, y, z, time) trajectories
- Automatic guidance and control of the aircraft along the trajectory
- Automatic response to command and control data link inputs
- Integration of the cockpit control and display functions with the trajectory generator, guidance/control and command/control functions.

Figure 2-1 illustrates the integration of these IFTC functions with the navigation and communication functions as well as the cockpit displays and controls and the aircraft flight controls. Digital processing is used to achieve the integration. The computer processes:

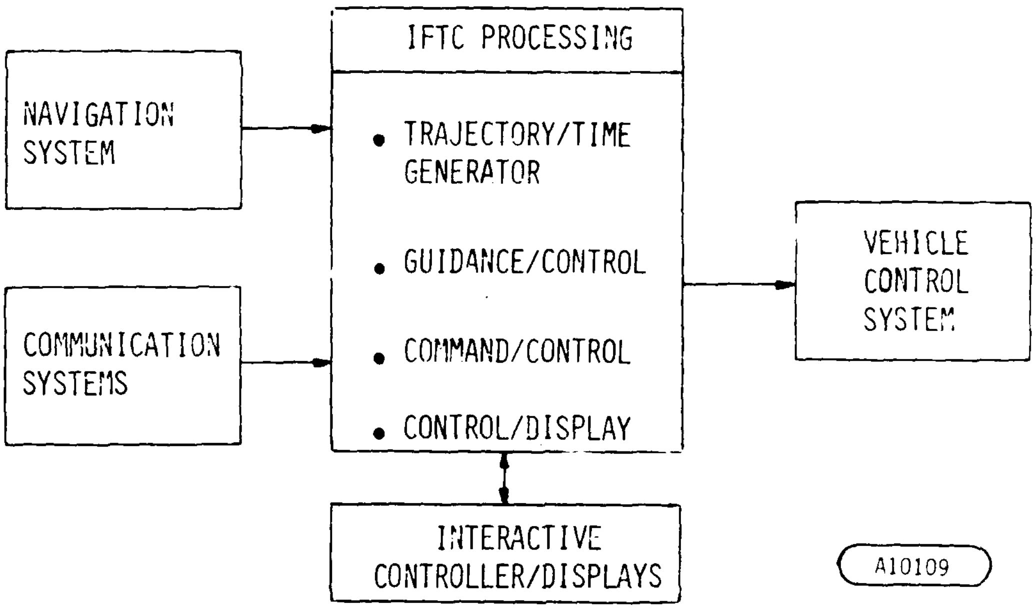
a. Aircraft position, velocity, and attitude inputs from the aircraft's navigation system

b. Tactical situation and command/control data from the data link communication system, and

c. Pilot inputs inserted through the interactive control/display hardware.

The trajectory generator computes the four-dimensional trajectory based on data defining the mission profile and known threat environments. The mission profile data consists of a sequence of points used to define the mission. These may be waypoints, targets, target initial points, refuel rendezvous points and approach points defined in the minimum by x, y, and z coordinates. For critical mission points the pilot may also specify a time-of-arrival (TOA) and speed. TOAs and desired speed are used as hard constraints by the trajectory generator to compute the speed and time profile.

THE IFTC OBJECTIVES WILL INVOLVE THE
INTEGRATION OF CONTROL-DISPLAYS-C^3 AND NAVIGATION



IFTC SYSTEM BLOCK DIAGRAM
FIGURE 2-1

After computation of the parameters completely defining the horizontal, vertical, and speed/time profile, the fuel use estimates for each profile segment are determined. The nominal profile is adjusted to avoid the lethal airspace around known threat emplacements. The aircraft performance capabilities, the operational limitations, control law authority, and predicted winds serve as constraints on the computed trajectory.

The guidance and control functions provide tracking of the nominal profile and maintain the speed and time schedule. This is accomplished by generating the differences between the navigation inputs, representing the current aircraft state, and the four-dimensional profile, representing the desired aircraft state. These differences, or errors, are processed to form commands to the servo systems for the ailerons, elevator, and throttle. The aircraft is controlled to minimize these errors.

Either automatic or manual modes of control are selectable, with independent selection between the pitch and roll channels and the throttle channel. The automatic mode relieves the pilot of performing the tracking tasks. Full manual control may be quickly assumed by the pilot, however, for rapid, unplanned mission activities such as jinking and bogie avoidance.

Pitch, roll, and throttle position commands are provided by the flight control laws and displayed on the attitude director indicator during manual mode operation.

The ease and confidence with which the pilot is able to use any advanced cockpit system determines the usefulness of the system. The pilot will consider the system useful if it reduces his workload in accomplishing his normal tasks, or if it allows him greater capability for completing a mission that would normally be aborted because of some increased workload. The goal of the control/display design was to minimize the number of pilot actions required to communicate with the IFTC system. Electronic displays, dedicated and multifunction keyboards, a hand-controlled cross-hair designator, and computer automation have been used to accomplish this goal.

An electronic situation display is used for displaying tactical data including the engaged flight profile, known and detected SAM and AAA envelopes, hostile and friendly aircraft locations, current aircraft position and track, and alternate flight plans. In addition to these classes of information which are displayed in symbolic form, aircraft track angle, map scale, ground speed, engaged plan number, assigned time-of-arrival and time-of-arrival error are displayed in alphanumeric format.

A second electronic display, the Status Display, is used for presenting alphanumeric information. The data is arranged in page format and the keyboard associated with this display is used for making data deletions, additions, or corrections.

Data link information is automatically processed by the computer and presented on the displays. This processing may be as simple as presenting hostile or friendly aircraft symbols and direction of flight (if known) on the tactical map, or as complex as processing the data associated with a command and control (C^2) mission re-direct, for which the trajectory generation capabilities are used for computing a direct, flyable profile from the current aircraft position to the first point in the redirect mission and all points, thereafter. If time-of-arrival is assigned at one or more points in the redirect mission, the time-velocity portions of the trajectory generator use these assigned values as hard constraints and attempt to construct a speed-time schedule, within its a/c control authority limits, to satisfy the times-of-arrival. If the arrival times cannot be satisfied, the pilot is notified immediately via the displays.

2.2 OPERATIONAL CAPABILITIES

The majority of the United States Air Force peacetime missions are flown in controlled airspace with a mix of civil and military aircraft. These missions are flown on well-defined, preplanned routes. Current cockpit equipment has sufficient capability to satisfy the demands of these missions. In times of conflict, however, when well-planned missions become chaotic as a result of enemy ground forces (AAA, SAMs) and aircraft, more capability is required.

The IFTC system has been designed with this volatile environment in mind. The trajectory generator accepts new points from the data link (C2) and computes a new, flyable trajectory after considering aircraft performance parameters, threats, and mission constraints. The Tactical Situation Display (TSD) is used to display the trajectory. Any newly computed trajectories are displayed in dashed format to distinguish them from the engaged profile. This presentation was selected to aid the pilot in recognizing that he has been directed to another target, or that a threat avoidance zone has been discovered in his engaged flight path.

The alternate profile includes a speed and time schedule for each flight segment as well as estimates of the fuel remaining at each profile waypoint. These computations would normally be estimated by the pilot if time or cockpit activity permitted, but these, as estimates, would be subject to human error. The automatic computation greatly relieves the pilot workload, and the availability of the data through the cockpit displays and the presentation of the new profile on the TSD allow the pilot to assess the situation quickly and make the final decision to comply or not to comply with the mission redirect request.

The redirect profile could also be initiated by the pilot using the cockpit keyboard and/or the crosshair controller to define a set of points for a new profile.

The capability for acceptance of the data linked information for display and automatic processing by the trajectory generator demonstrates the potential for a significantly greater amount of pertinent tactical information the pilot can receive and evaluate. This automation is accomplished while preserving the philosophy of allowing the pilot to review the incoming data and be the final decision-maker. Without this capability the requirements for the manual insertion of incoming data would exceed the pilot's capacity.

The parameters that can be specified for each point of the trajectory are not limited to latitude, longitude, altitude, and time, but may include heading at flyover, flight path angle, turn radius, and speed. The specified parameters are used as constraints by the trajectory generator. The advantages of this capability are especially evident for weapon delivery missions under low visibility conditions in which the aircraft's heading, flight path angle, and speed must be controlled along the desired delivery path. Without the trajectory generator and the automatic control system, significant workload is placed on the pilot to perform the navigation and control.

Since it is anticipated that the battle zones of the next conflict will be highly saturated with SAM or AAA emplacements, the IFTC threat avoidance capability would provide a crucial benefit. Present mission planning methods require the pilot/navigator to structure the route to avoid known defensive emplacements. When evasive maneuvers are performed to avoid in-flight detected bogies and ground threats, it is highly probable that the pilot would lose his position relative to the planned profile.

In addition, any time scheduling is severely impacted. The IFTC system will allow the pilot to continue to have full manual control of his aircraft for performing defensive/offensive maneuvers, and will aid him by computing an intercept (or capture) profile back to the original profile. This intercept profile is continuously updated and displayed on the TSD. Included in this recomputation are the estimates of times-of-arrival, speeds, and fuel reserves for each remaining point in the mission. This data is available for transmission on the C^2 data link net to aid in the utilization of the strike forces.

In addition to the increased capabilities afforded by the IFTC system in a C^2 environment, many of the same capabilities are applicable to autonomous or near-autonomous operation. In the absence of data-linked information, the pilot may still respond with minimum effort to voice communication with forward area controllers. The controls and displays may also be used effectively to modify the existing flight plan as a result of pilot-initiated changes.

In summary, the operational benefits afforded by the system will meet the requirements for a quick-reaction, precision time-space control system while providing the flexibility for command and control redirects. The pilot workload is limited to a level that should not exceed that presently encountered in either fighters or transports.

Section 3 gives a step-by-step description of the use of the IFTC system during the execution of a penetration mission with blind weapon delivery on two targets. The mission includes such unplanned events as a weather diversion, hostile bogies, a C^2 mission redirect, and the appearance of SAMs on the nominal flight plan. Also included is a coordinated air attack on a target, requiring precise time coordination with a wingman.

3 DEMONSTRATION SCENARIO

The algorithms developed for the IFTC system were programmed in the Lear Siegler Instrument Division Hybrid Computing Facility computers (Figure 9-1). The simulation configuration is shown in Figure 9-2 and described in Section 9.

Real-time processing of the algorithms in the hybrid computers made it possible to perform pilot-in-the-loop testing. A representative fighter aircraft (F-4E) dynamic model was used in the simulation and the IFTC outer-loop control law outputs and the pilot inputs were coupled to the aircraft control surfaces using the stability augmentation and fly-by-wire system developed for the F-4 under the 680J Survivable Flight Control System program[3]. The details of the 680J are shown in Appendix B and the aircraft model description is given in Appendix A.

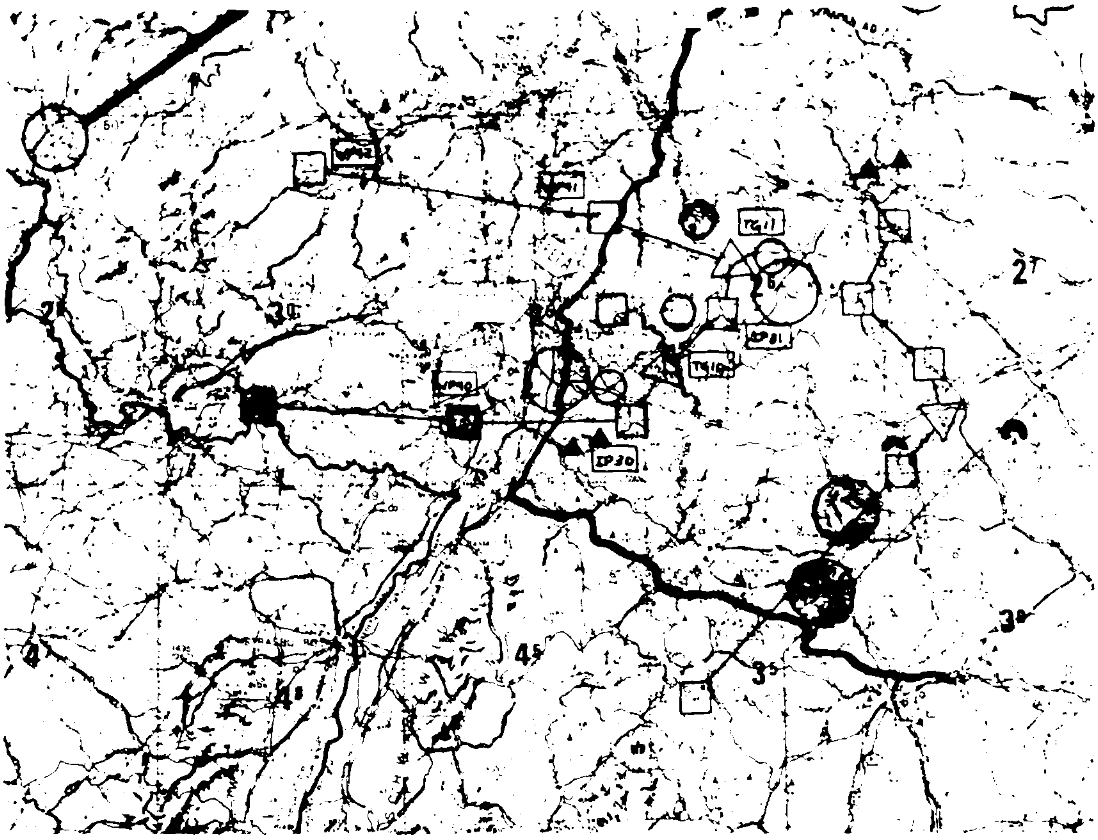
For purposes of demonstrating the IFTC concept, a representative, medium-altitude, blind weapon delivery mission was constructed in concert with Air Force TAC pilots.

3.1 MISSION PLANNING

The mission area selected was central Europe with the forward edge of the battle area (FEBA) chosen as the geographic boundary between Eastern and Western Germany (Figure 3-1). The mission begins at Zweibrucken, approximately 50 nm from the FEBA, at an altitude of 8000 feet and an airspeed of 420 knots. A critical time-of-arrival (TOA) was assigned at the first IP (IP30), as was a desired heading of 15 degrees and a ground speed of 420 knots. These specified parameters became hard constraints for the trajectory generator, and the four-dimensional profile created satisfied these constraints.

The mission as described in the mission planning briefing was a low-to-medium altitude (not terrain following), blind weapon delivery on two targets; the first, TG10, a transmitting tower and the second, TG11, a small hydroelectric plant. Both targets are indicated by the conventional triangular ($\triangle$) shape. Navigation and IP points are indicated by squares ($\square$). The circular regions represent SAM and AAA kill envelopes. These were modeled simplistically as vertically oriented cylinders, and for simulation purposes the number of SAM and AAA emplacements was kept small.

The mission data is presented on the cockpit displays as shown in Figure 3-2. Note that the TOA assigned at IP30



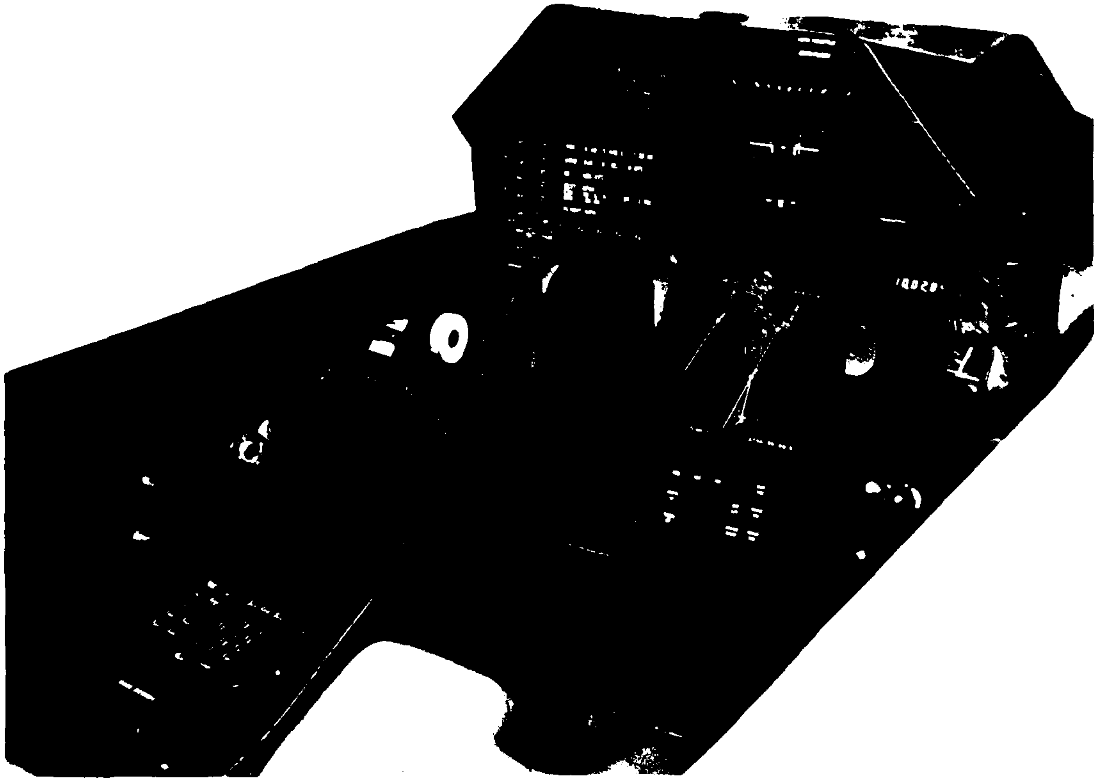
DEMONSTRATION MISSION PROFILE
FIGURE 3-1

can be satisfied, and the pilot determines this by observing that the ΔTOA displayed on the lower right side of the TSD indicates " ΔTOA = 00:00L", which is interpreted to mean that the time-of-arrival error is estimated to be 0. seconds (L, indicating "late", is meaningless in this case).

3.2 UNPLANNED DEVIATIONS

3.2.1 Weather Diversion

Immediatly after the start of the mission an intense weather system is detected, centered at approximately the location of Landau. The first question that confronts the pilot is, "Can the weather system be avoided by modifying



MISSION PROFILE AND DATA ON COCKPIT DISPLAYS
FIGURE 3-2

the flight plan and still meet the TOA at IP30?" This question is answered by the following control display actions:

a. Cross-hair (X-hair) is activated by depressing cross-hair controller on top of throttle. Map is automatically placed in North-up, plot-stabilized mode.

b. X-hair, now visible on map, is slewed to approximately the position of waypoint 40 (close to Landau) and the center-on-X-hair button on the TSD controller is depressed. This action centers the TSD display at the X-hair location for better visibility. This step is not always required, since it depends upon map scale and the aircraft position with respect to the profile points that are to be modified.

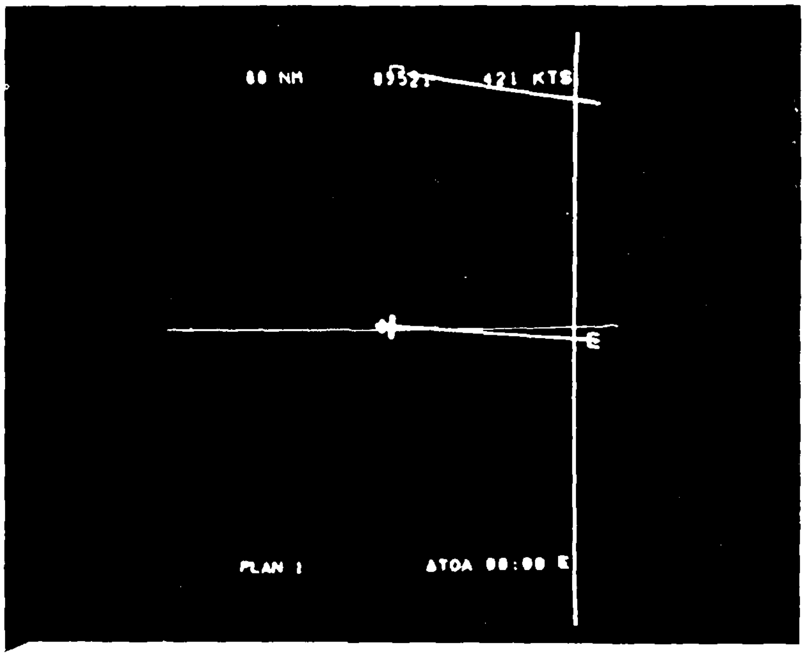
c. The pilot's objective, now, is to designate (or "hook") WP40 and move it clear of the weather system, but do so without affecting the remainder of the mission profile.

d. The X-hair is activated again and moved to lie over the existing position of WP40. A map scale of 40 nm or 80 nm works best for this operation to provide good resolution. X-HAIR INSERT is depressed. (X-HAIR INSERT is located on top of the throttle, above the X-hair controller as shown in Figure 7-10. It is thumb activated).

e. After the X-HAIR INSERT switch is depressed, the computer begins a search of all defined navigation points, including targets, IPs and rendezvous points. If the X-hair was placed within 2 nm of WP40 (step d), the computer recognizes that fact and indicates on the status display that WP40 has been selected. Also indicated is the plan number which contains WP40, in this case, Plan 1. If the search does not detect proximity of the X-hair with a defined point, that fact is indicated on the status display by the message, "NO POINT SELECTED".

f. The X-hair remains on following step e, and with a successful designation of WP40, the X-hair may now be slewed, *moving WP40 to a new position. In this* case, WP40 is moved to clear the severe weather system. XHAIR INSERT is depressed following the movement of the X-hair to the new position. Figures 3-3, 3-4, and 3-5 show the displays as steps a through f are performed.

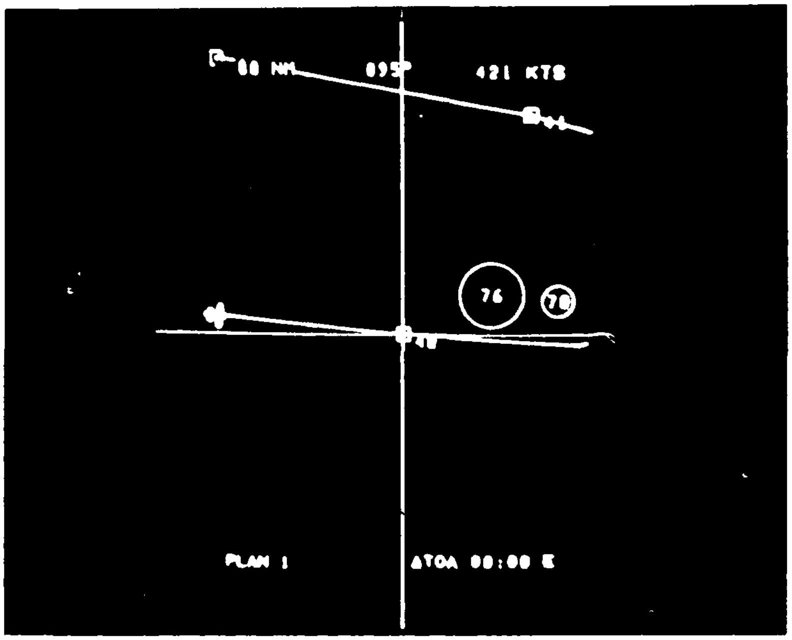
g. Following the X-HAIR INSERT depression, the computer recognizes that the pilot's intent is to move WP40. The new coordinates are stored and a new four-dimensional flight plan is computed, including the speed/time dimension, to satisfy the TOA assigned to IP30. Within seconds (2-3), the new profile is drawn on the TSD (Figure 3-6) in dashed, predictive format. The original profile is left on the TSD in solid line format, indicating to the pilot that, at this point in the process, the original profile is being tracked by the flight control system. A new line of information appears on the TSD: P ΔTOA = 00:00L. This information indicates to the pilot that under the aircraft dynamic constraints used by the trajectory generator and the control authority limits given to the flight control system, the TOA at IP30 may still be satisfied. The pilot should



X-HAIR POSITIONED FOR CENTERING DISPLAY
FIGURE 3-3

expect, however, that his nominal ground speed will increase to account for the increased path length added by the weather diversion.

h. The modified profile has been assigned a new plan name and the NAV SEL page has been automatically placed on the status display. The pilot may now engage the new profile and couple it to the automatic flight control system by simply depressing the ENGAGE key on the flight mode panel on the status display. If further information about the new plan is needed, the pilot simply depresses DATA rather than ENGAGE. This action causes the index page for the new plan to be displayed. From this page the pilot may select a specific point in the plan using the row-column selector buttons. DATA is depressed again and the pages for specific data relating to the designated point are now displayed. This step would be used to check estimated fuel reserves at the refuel point to determine the effects of the path stretch around the weather system.

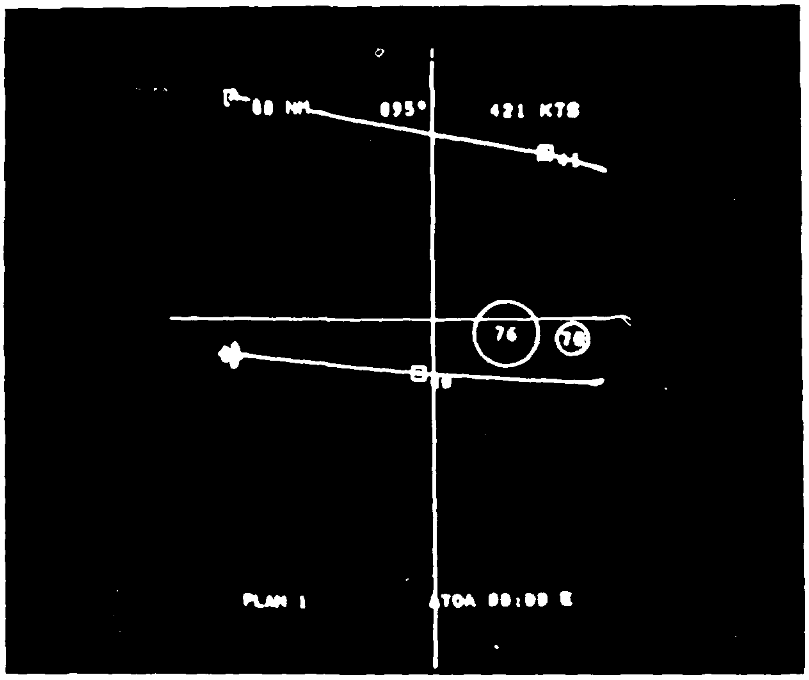


TSD REPOSITIONED - X-HAIR SLEWED TO WP40 AND INSERTED
FIGURE 3-4

i. When the ENGAGE key is depressed, the original profile is erased and replaced by the modified profile, as shown in Figure 3-7. If automatic flight control is selected, the aircraft will respond immediately by flying the new profile.

Note that a new waypoint, WP43, was created and added to the mission list. This point was added near the perimeter of SAM envelope 72. The trajectory generator, in conjunction with the AVOID algorithm, generated the new point to prevent the intersection of the modified profile and the SAM lethal envelope. This intersection would have occurred had the profile been constructed from WP42 to IP30. The details of the AVOID algorithm are discussed in Section 5.

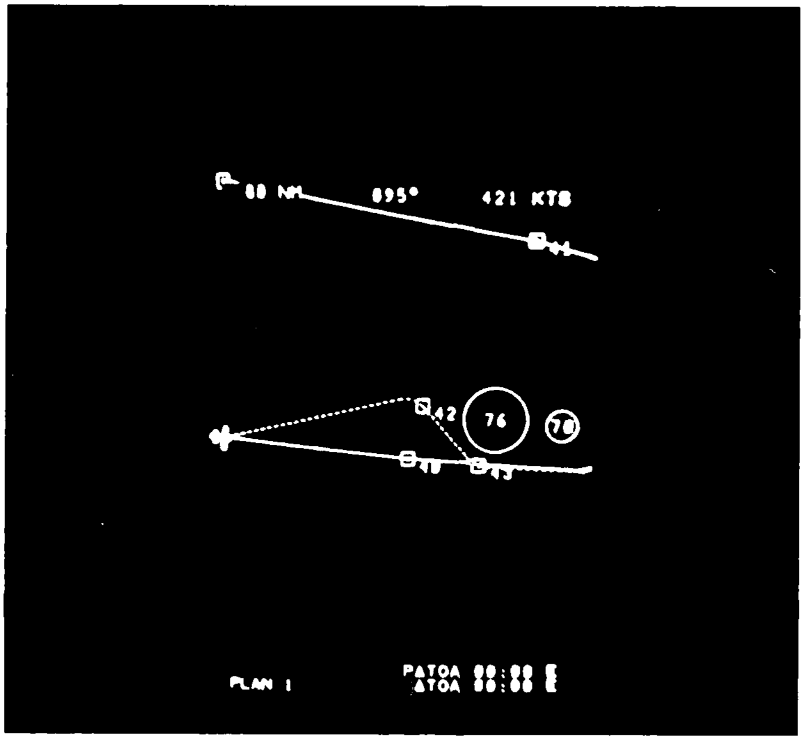
Although approximately nine operations are required to modify the profile as just described, once familiarity with the system is gained, the entire sequence may be performed in less than one minute. At no point in the process was the alphanumeric keyboard required to key in specific waypoint coordinates.



WP40 SUCCESSFULLY "HOOKED" AND MOVED TO NEW POSITION
FIGURE 3-5

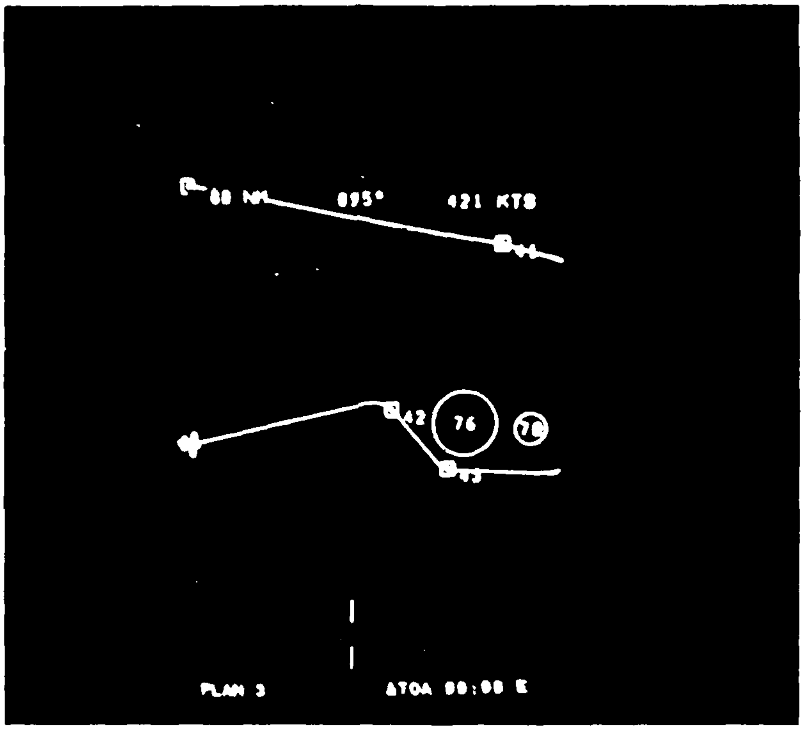
3.2.2 <u>Hostile Aircraft</u>

As the mission progresses, the next unplanned event occurs just after fly-by of WP43 and just prior to crossing the FEBA. At this time the IFTC aircraft has been alerted by the data link system to two hostile bogies at about 1 o'clock high and a distance of about 25 miles. The DATA LINK light on the glare shield is illuminated. Because it is in the area of the pilot's normal scan, it attracts his attention and serves to cue him to check his TSD. On the TSD in flashing format are symbols representing the aircraft positions, direction of flight, and the fact that they are hostile. (See Figure 3-8.) TSD symbology for nav points, targets, IPs, friendly and unfriendly aircraft were chosen to be compatible with the set of unclassified symbology selected by the JTIDS symbology study committee[ ]. Since the publication of that committee's preliminary report, certain changes have been made to the recommended symbology. These changes have not been incorporated in the simulation.



MODIFIED PROFILE PROVIDING DIVERSION AROUND WEATHER
FIGURE 3-6

Following a quick assessment of the situation, the pilot switches off the pitch and roll channels of the automatic flight control system to allow full manual operation in these channels. Switching of both axes is accomplished by depression of a thumb switch on the control stick (Figure 7-9). The aircraft is flown manually until it is determined that the hostile bogies pose no threat. If desired, the pilot may transpose the A/C position to the center of the TSD. This allows a better rearward field-of-view in the event that the bogies should attempt an attack from behind.



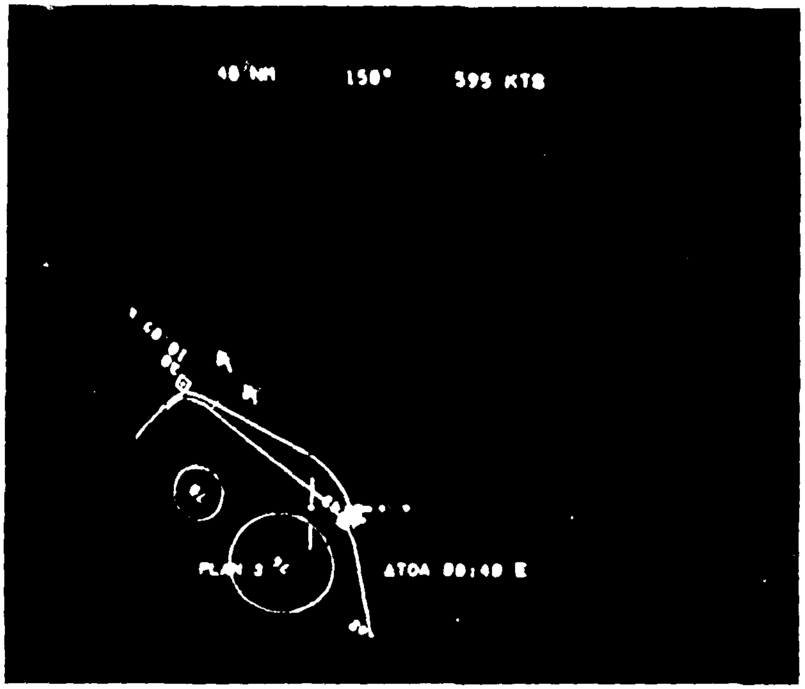
MODIFIED FLIGHT PLAN, INSPECTED BY THE PILOT AND ENGAGED
FIGURE 3-7

Two major activities occur in the computer during this evasive action:

a. The guidance equations detect a significant deviation from the nominal flight flight plan and set a flag when this occurs.

b. The trajectory generator recognizes that the guidance function of step (a) has occurred and computes a transition (or capture) trajectory from the current aircraft position to the next point in the mission list. This capture trajectory segment is linked to the remainder of the mission by recomputing the entire four-dimensional trajectory, beginning with the aircraft position and ending with the last point in the mission list.

This last step is significant because recomputation of the entire profile includes the speed/time scheduling, fuel



HOSTILE BOGIES SHOWN ON TSD - PILOT BEGINS DIVERSIONARY MANEUVER
FIGURE 3-8

usage estimates for each flight segment, and updated time-of-arrival estimates. Because of this the pilot is immediately alerted to late or early times-of-arrival, or low fuel reserves at any point in the mission.

Notice in Figure 3-8 that as the pilot has deviated from his original mission, the capture profile has been automatically computed and drawn on the map. As the pilot continues to deviate from the mission, the capture profile is continually recomputed. When the cause of the deviation has ceased to be a threat, the pilot knows exactly the path that will be followed to the original profile when the automatic flight control system is re-engaged or the flight director cues are followed. He also immediately knows any impact on the ability to maintain the TOA as a result of the mission deviation. Because the deviation caused by the hostile bogies occurred very close to IP30, the point for which the TOA of 10:09:00 was assigned, the TOA can no longer be met and the IFTC system has indicated on the TSD that the pilot can expect to be 19 seconds late. This is indicated to the pilot on the TSD by " ΔTOA = 00:19:L" in the lower right corner of the display.

To understand that the TOA cannot be satisfied, remember that the trajectory generator and guidance/control algorithms operate within certain aircraft control constraints and are limited in the degree of control authority that can be imposed on the aircraft control systems. These limits are discussed in detail in Sections 5 and 6, and include such things as maximum and minimum airspeeds, acceleration and deceleration limits, and bank and flight path angle limits. Using the extremes of the limits, the trajectory generator computes a maximum and minimum time-of-arrival for each point in the mission list. This may be thought of as an arrival-time window. It represents the earliest and latest time that the aircraft could arrive at the point. If the time and distance from the aircraft to the point in question is large, the arrival-time window is large. This is true because the control extremes, either maximum or minimum, may be applied for a longer time period, and therefore have a larger effect.

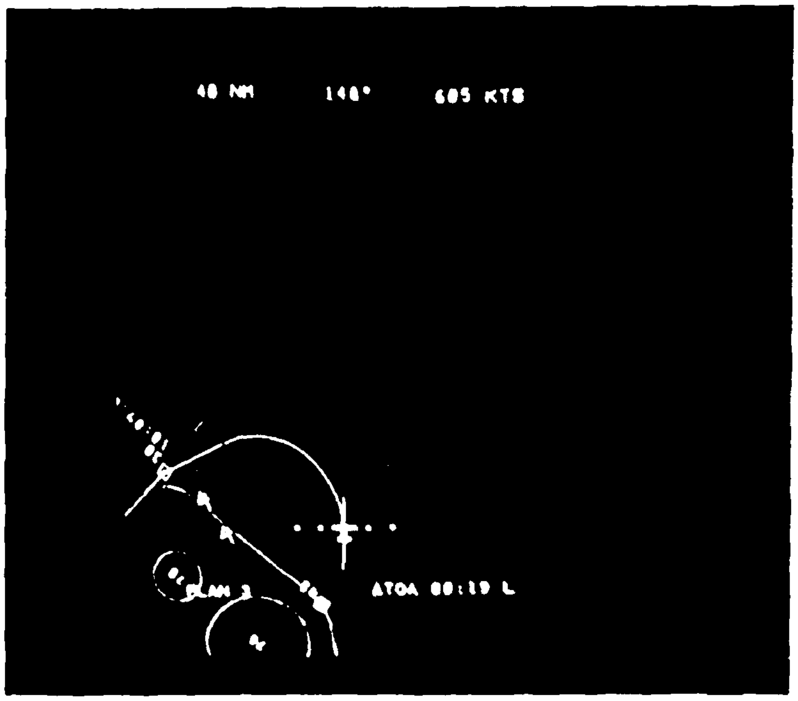
Conversely, as the distance and flight time between the aircraft and the point in question shorten, the control action extremes can be applied for a lesser length of time and the arrival-time window becomes smaller. When the assigned time-of-arrival (TOA) of the aircraft at the waypoint in question lies within the computed time-of-arrival window, the error in the TOA is displayed as zero (0.) and the aircraft is controlled to satisfy the TOA following the speed/time profile.

If the assigned TOA is not bounded by the minimum and maximum times-of-arrival, the TOA error will not be zero, and the TOA cannot be satisfied. The TOA error (ΔTOA) is then displayed as the difference between the TOA and the minimum or maximum TOA, whichever is appropriate. An E (early) or L (late) will be correspondingly displayed with the error.

In Figure 3-9, the pilot has determined that the hostile aircraft no longer pose a threat to his mission. The automatic flight system has been engaged and the aircraft is being controlled along the capture trajectory to IP30.

3.3 WEAPON DELIVERY

After flyover of IP30, the pilot must "set up" for performing blind weapon delivery on TG10. The target coordinates, elevation, heading, bomb type, number, and spacing have been specified and loaded into the computer as a part of the mission briefing and planning exercises. These parameters may be changed manually, however, using the keyboard and the status display. If target designation

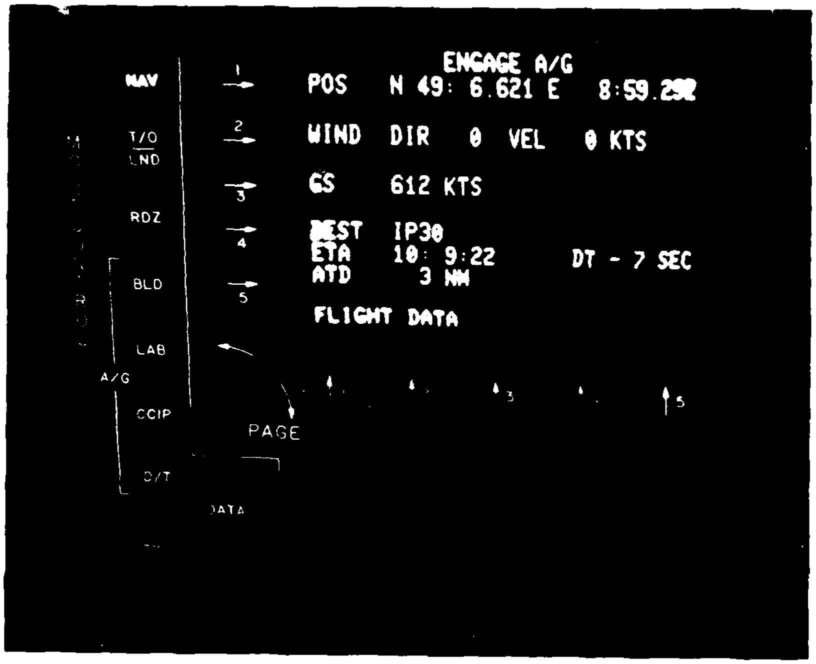


PILOT COMPLETES DEVIATION AND RECOUPLES AUTO-FLIGHT SYSTEM TO FOLLOW CAPTURE TRAJECTORY BACK TO FLIGHT PLAN - TSD INDICATES THAT TOA CANNOT BE SATISFIED
FIGURE 3-9

and tracking capability are available (high resolution radar), the target coordinates may be updated automatically prior to weapon release. While designation and tracking of the target are not a part of the simulation, the effects of updating the target coordinates during the weapon delivery run-in are included.

The top line of the status display is reserved for advisory messages, automatically placed there by the IFTC system regardless of the page being displayed at that time. As fly-over of the IP occurs, "ENGAGE A/G" is displayed to cue the pilot to set up for air-to-ground weapon delivery. The system computer initiates the display of this message recognizing that a target is the next point in the mission list. Figure 3-10 shows the "ENGAGE A/G" cueing message on the status display as the aircraft approaches the IP point.

To set up for Blind mode weapon delivery, the pilot depresses the BLIND mode key. This results in the display of the

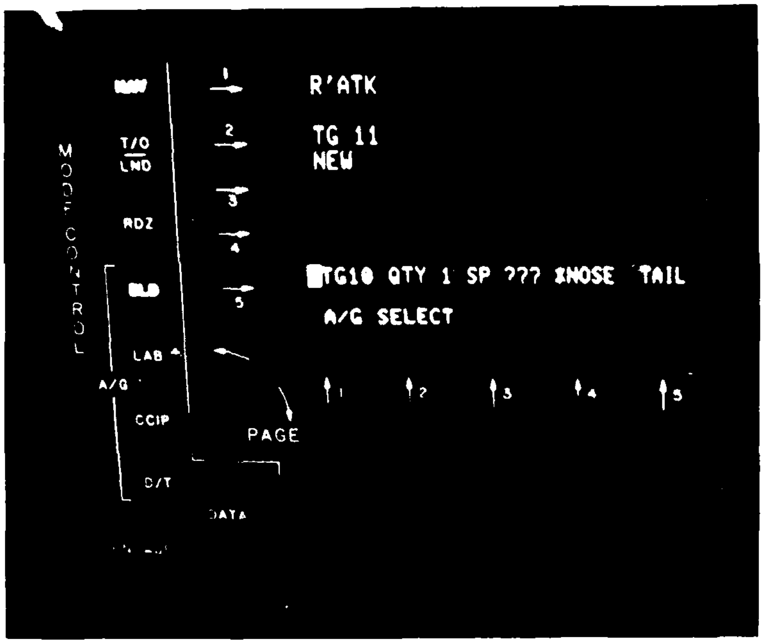


PILOT IS CUED BY THE STATUS DISPLAY TO ENGAGE THE AIR-TO-GROUND WEAPON DELIVERY MODE AS THE IP IS CROSSED
FIGURE 3-10

Blind Select page of the status display as shown in Figure 3-11. The computer has anticipated the engagement of TG10 and placed the cursor accordingly.

Normally, the pilot would depress ENGAGE. When the computer recognizes this action, the IFTC functions pass control to the weapon delivery release and steering functions. The handoff is performed carefully to eliminate any control system transients.

Engagement results in a switching of the throttle and pitch control channels from automatic (if previously selected) to manual. Roll steering is performed automatically unless deliberately switched to manual; however, pitch control is manual to allow the pilot several options during weapon delivery.



PILOT USES BLIND SELECT PAGE TO INITIATE WEAPON DELIVERY - SYSTEM ANTICIPATES DELIVERY ON TG10 AND AUTOMATICALLY PLACES CUEING CURSOR AT TG10

FIGURE 3-11

As run-in toward the target proceeds, the pilot flies the pitch channel manually, maintaining a constant altitude, wings level approach to the target. When the IN-RANGE annunciator on the glare shield illuminates, the pilot may exercise three options:

a. Begin an up to 4g pullup maneuver - Release will be automatic.

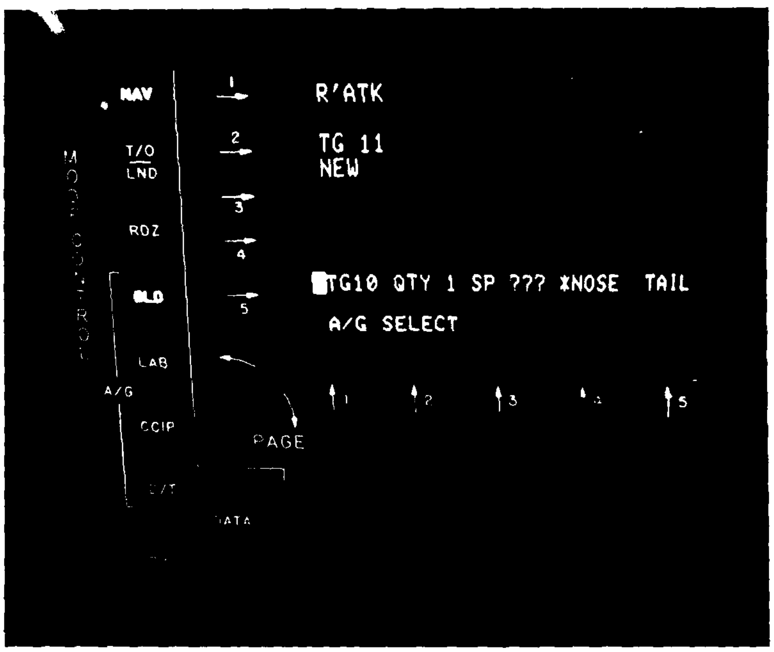
b. Continue flying at essentially a constant altitude - Release will be automatic.

c. Manually follow the pitch steering needle (horizontal) - This will result in a shallow dive with release occurring automatically and just prior to reaching the pre-selected break-altitude.

The weapon delivery run continues with the PICKLE button (bomb release) depressed (Figure 7-9), until the WEAPON

RELEASE annunciator illuminates. This indicates that a successful release has occurred. The trajectory generator also recognizes the release signal and initiates the generation of a new profile from the weapon release point to the next point in the mission (IP31). Unless the next point is a target, control is passed from the weapon delivery functions back to the IFTC nav steering functions. This is indicated to the pilot by the extinguishing of the Blind mode key and the lighting of the Nav mode key. If the next point is a target, the system remains in the Weapon Delivery mode.

The Blind Select page (Figure 3-12) is used to provide additional system capability. TG10, TG11, NEW or R'ATTK (re-attack) may be selected using the row keys. TG11 is the next target in the sequence and could have been selected to rapidly initiate a bypass of TG10 and a direct fly-to to IP31 and TG11. NEW is used with the keyboard for entering the identifier of any other target whose coordinates and weapon delivery parameters have been stored in the computer.



BLIND WEAPON DELIVERY MODE SELECT PAGE
FIGURE 3-12

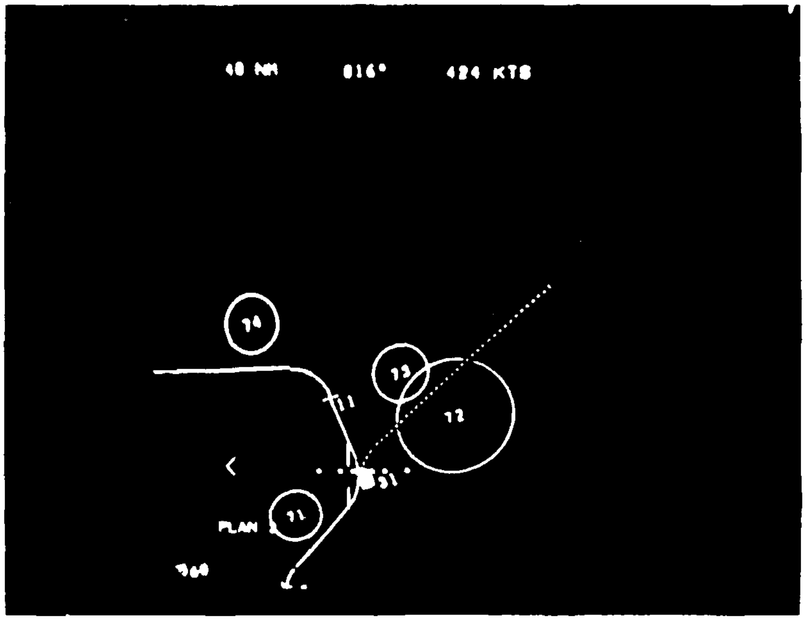
R'ATTK is a special function which provides the pilot with the capability of rapidly initiating a re-attack on the current target. Though not mechanized in the simulation at this time, it was included in the control/display and weapon delivery design with the purpose of selecting a new, random heading for a subsequent pass at the same target. The pilot designates R'ATTK with the proper row key, depresses ENGAGE, and the a/c is flown automatically (if selected) along the curved, re-attack trajectory which is also drawn on the TSD. Manual control may also be performed by following the steering cues on the ADI.

The mission continues under IFTC control to the next profile point, IP31. As previously described, the pilot is cued on the status display to set up for air-to-ground weapon delivery as fly-over of IP31 occurs.

3.4 MISSION REDIRECT

Soon after the pilot has completed the setup for weapon delivery on TG11, a mission redirect is passed to the IFTC system via a simulated JTIDS-like data link. A complete description of the data link simulation is given in Section 8. The pilot is first made aware of the request for a redirect by the illumination of the DATA LINK light. As his attention is drawn to the TSD, he observes a dashed-line trajectory segment beginning at his aircraft position and disappearing to the right side of the display, as shown in Figure 3-13. Because of the TSD scaling, most of the redirect information is not on the map. The pilot is further aided by the IFTC system, however, with the advisory message on the status display, "C & C PLAN REDIRECT", indicating that command and control has issued a mission redirect. The system has accepted the points, generated a four-dimensional trajectory through them, including fuel estimates, arrival time windows and ETAs, and linked the new mission profile with the current aircraft position. This new trajectory, resulting from the redirect, is assigned a plan number and the NAV SEL page is automatically displayed with the cursor over the new plan number. If one or more arrival times were specified as part of the redirect information, the trajectory generator would attempt to satisfy them within its control authority. The entire process, from receipt of redirect, processing, and display of the profile on the map, is accomplished in less than five seconds.

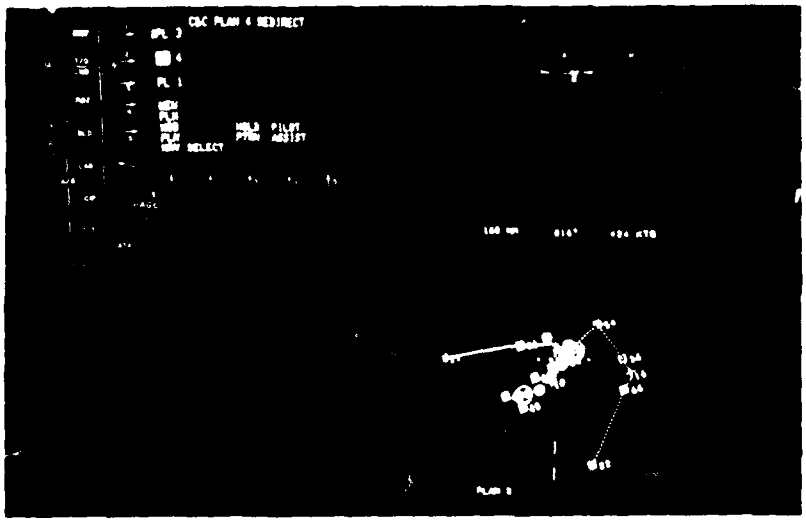
After understanding that he had just been given a redirect by command and control, the pilot increases the TSD scaling until the entire redirect profile is visible (Figure 3-14). The entire redirect profile may be seen in perspective with



PILOT'S FIRST VIEW OF C^2 MISSION REDIRECT
FIGURE 3-13

the original flight plan. The redirect plan consists of five points, including an IP, target, egress, and refuel point. The redirect is drawn in dashed line format, indicating to the pilot that it has not been engaged by the flight control system. That decision is always reserved for the pilot.

The pilot is aided in making this decision by the estimated fuel remaining and time-of-arrival computations available to him through the displays.



TSD SCALING IS REDUCED AND ENTIRE
REDIRECT MISSION IS VISIBLE
FIGURE 3-14

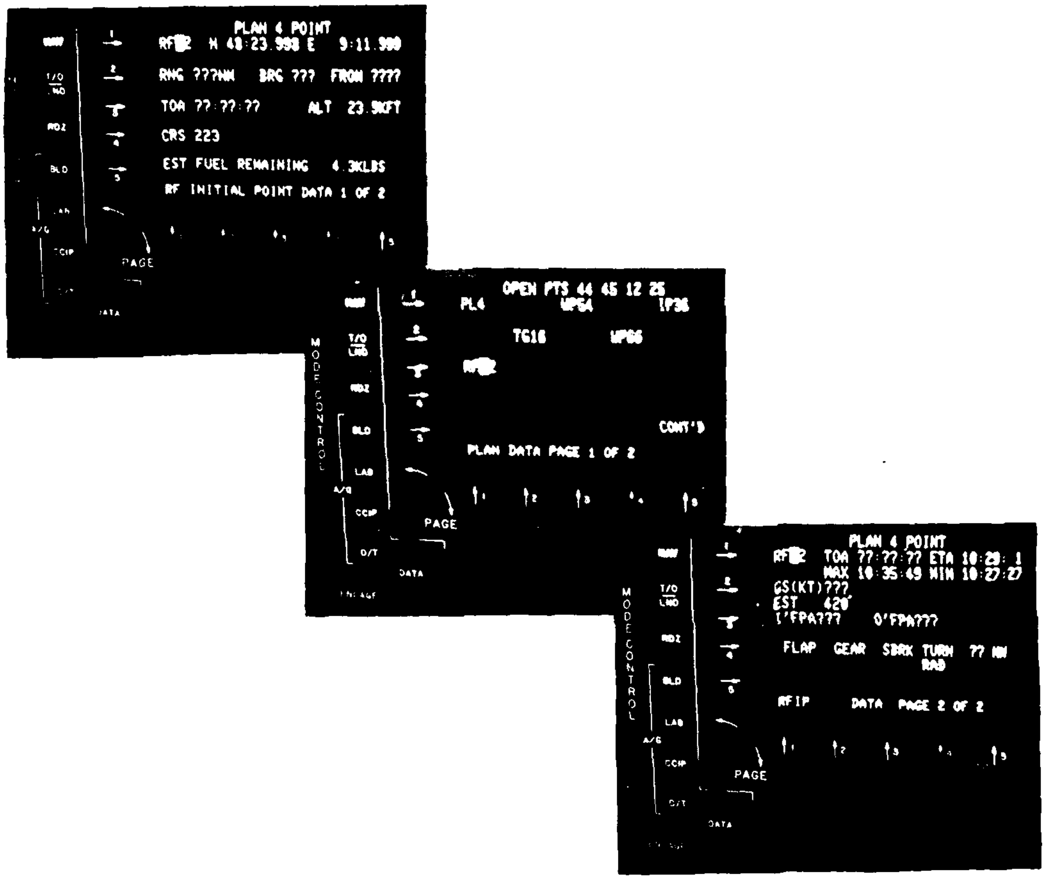
As an example, the pilot may use the displays to check his fuel reserves and arrival time estimates at the redirect refuel point by the following steps:

a. Depress DATA with the NAV SEL page on the status display and the cursor on PLN[3] (automatically accomplished by the display logic of the IFTC system). The plan index for the redirect plan is displayed (Figure 3-14).

b. The row-column keys are used to place the cursor over RF22.

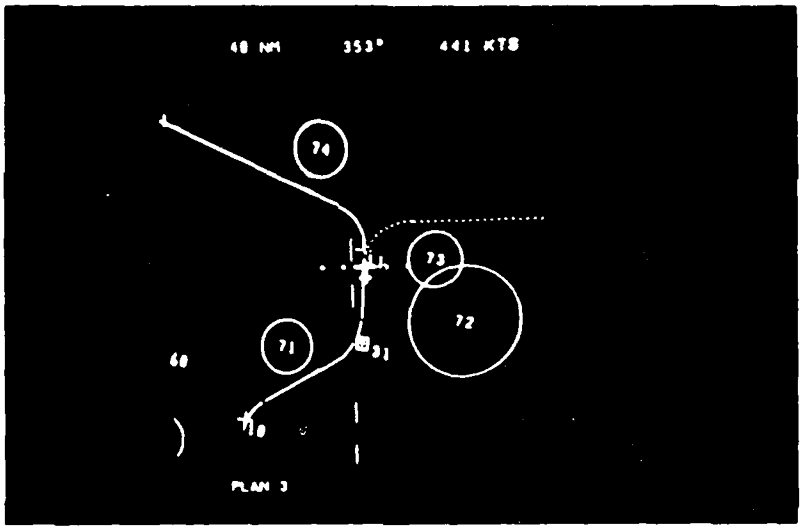
c. DATA is depressed. This results in the display of the specific data for RF22. Page 1 and Page 2 are shown in Figure 3-15. The pilot may use the PAGE FORWARD - PAGE BACKWARD lever switch to step through the data pages for the other points in the plan, without the necessity of returning to the index page and selecting another point.

Satisfied that his fuel reserves at the newly assigned refuel point are sufficient, the pilot elects to comply with the redirect and engage the new profile. Depression of the ENGAGE key with the NAV SEL page on the status display will engage the redirect profile. If the NAV SEL page is not on the status display, depression of the Nav mode select key will cause it to be displayed.



PILOT USES STATUS DISPLAY TO CHECK FUEL RESERVES AND ARRIVAL TIME ESTIMATES AT REFUEL POINT FOR MISSION REDIRECT
FIGURE 3-15

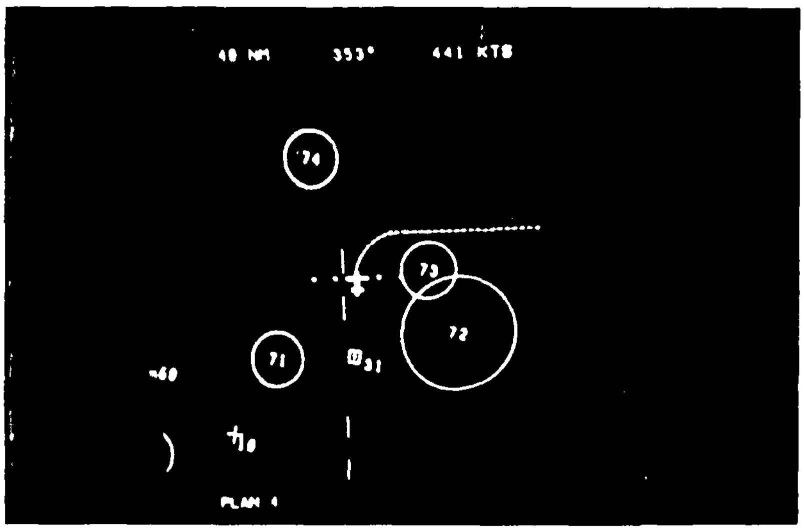
In this situation the pilot elects to delay engagement of the redirect until the initial trajectory segment from the aircraft to WP54 passes clear of the SAM threat envelopes (Figure 3-16). SAM threat avoidance is not automatically performed for the capture trajectory segments. As the aircraft continues to fly the original profile, the capture trajectory is continually recomputed, recognizing that the aircraft's position is changing. The updated TSD is used by the pilot to determine when the clearance is satisfied.



CAPTURE TRAJECTORY TO MISSION REDIRECT IS CONTINUALLY RECOMPUTED - THREATS ARE CLEARED AND PILOT ELECTS TO ENGAGE THE REDIRECT PROFILE
FIGURE 3-16

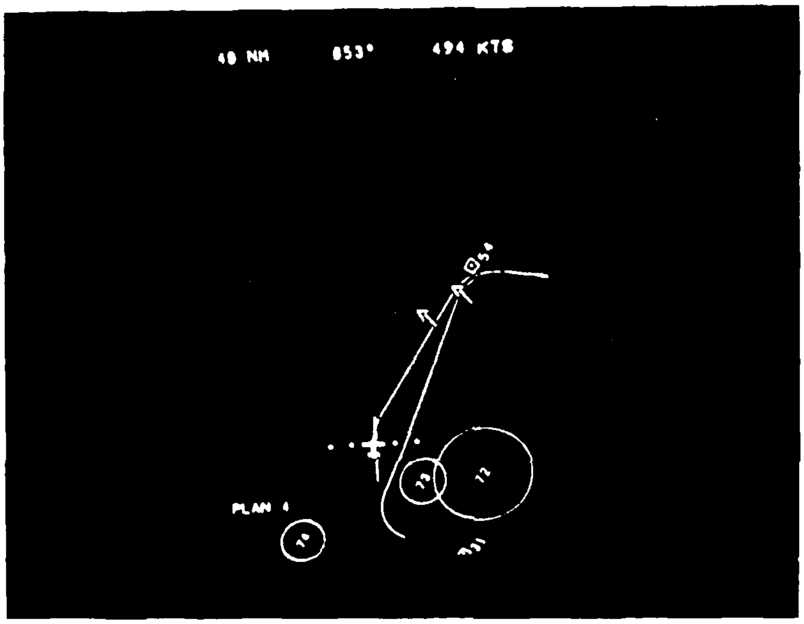
Engagement of the new profile results in the erasure of the old and the redrawing of the new in solid line format. If the autoflight system is engaged, the aircraft will immediately begin to fly the new trajectory (Figure 3-17).

After completing the execution of the first turn on the redirect mission, the pilot is jumped by two more hostile bogies. The actions taken by the pilot and the sequence of events is nearly the same as described previously. The pilot deviates from the nominal redirect plan, the IFTC system recognizes this, capture profiles are generated and drawn on the map, and this entire process continues until the bogies no longer pose a threat and the automatic



MISSION REDIRECT ENGAGED
FIGURE 3-17

flight system is re-engaged. The aircraft is then flown by the most direct route to WP54, as shown in Figure 3-18.

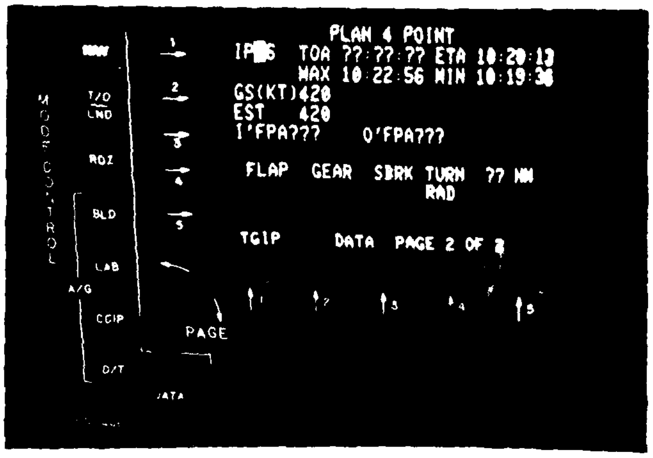


CAPTURE PROFILE TO NEXT WAYPOINT
FIGURE 3-18

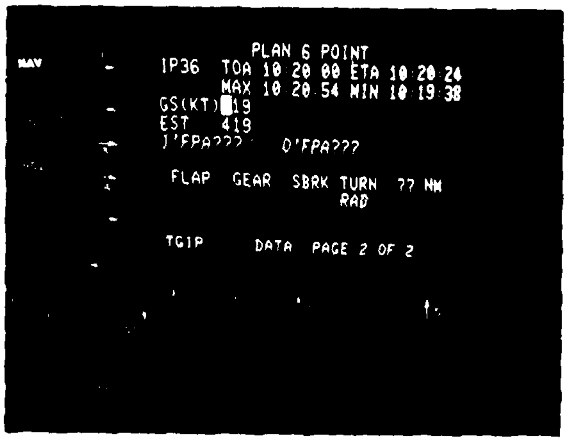
3.5 COORDINATED WEAPON DELIVERY

After fly-by of WP54, the pilot uses UHF radio to contact a wingman. The purpose of the contact is to coordinate the timing for a combined air attack on TG16. The objective is to have both aircraft attack the target on different headings and within 15 seconds of each other. The MIN TOA and MAX TOA values for IP36 are used to aid in the time coordination process, with the assurance that any arrival time selected for IP36 within the MIN and MAX TOA range could be satisfied by the trajectory generator and guidance control functions.

The status display is used to retrieve the data for IP36. Page 2 of the data for IP36 (Figure 3-19) displays the MIN and MAX TOA as well as the ETA. Note that the ETA is within the MIN and MAX TOA values, as would be expected. The pilot and wingman agree that the wingman will make first pass over the target. A time is picked and the pilot enters it as a TOA as shown in Figure 3-20.



PILOT USES STATUS DISPLAY FOR SELECTING ARRIVAL TIME
FOR COORDINATED ATTACK
FIGURE 3-19

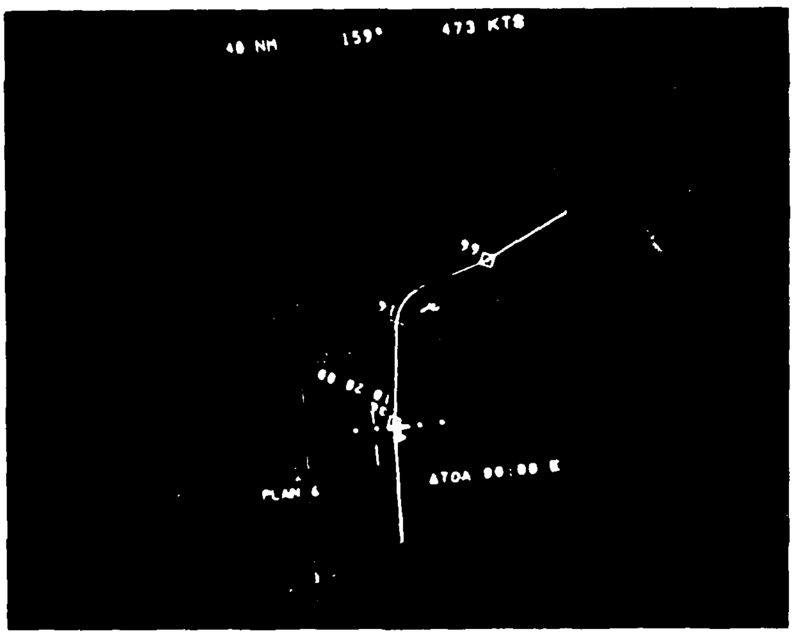


ARRIVAL TIME IS INSERTED AS A TOA
FIGURE 3-20

ENTER is depressed and the profile is recomputed with the TOA, just entered, as a hard constraint. The horizontal and vertical profiles are as before, but the speed/time schedule is adjusted to satisfy the TOA.

The mission continues, with the roll and pitch channel commands controlling the aircraft along the horizontal and vertical portions of the trajectory, and the throttle channel controlled to follow the speed and time profile. This relieves the pilot of the time-consuming task of continually recomputing or monitoring his ETA and making appropriate speed adjustments for corrections.

If the aircraft state information for the wingman is available on the data link, the IFTC system will process that information and display it on the TSD using the friendly aircraft symbology[10], as shown in Figure 3-21. The



WINGMAN APPEARS ON TSD AND MOVES ACROSS THE TARGET
AS IFTC A/C BEGINS W/D RUN-IN
FIGURE 3-21

pilot uses the same procedure as described previously for setting up the weapon delivery on TG16. As the run-in to the target progresses, the wingman symbol is updated on the TSD as it moves across the target in front of the IFTC aircraft.

The IN-RANGE light illuminates at the proper time, the PICKLE button is depressed and the WEAPON RELEASE light illuminates when the bomb (or bombs) is released, and the weapon delivery run is completed.

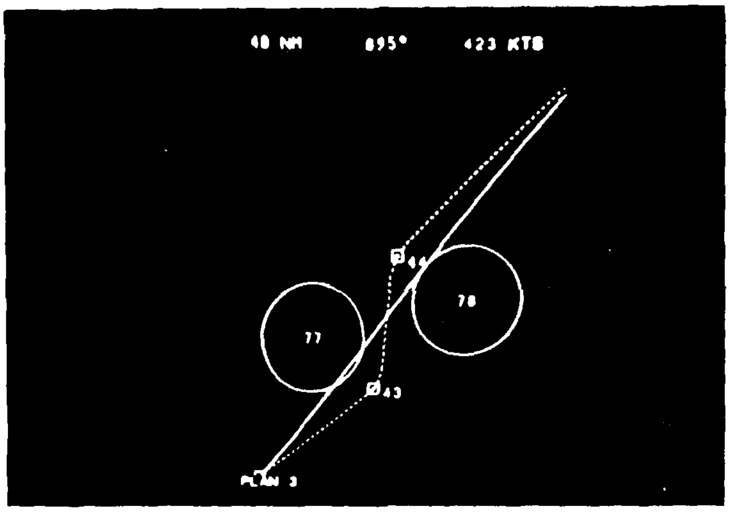
3.6 THREAT UPDATE AND AVOIDANCE

Just after the turn towards the egress point, WP66, is completed, two previously unknown SAMs are activated. This information becomes available either through the data link or through detection by on-board sensors. The pilot is first alerted to the situation by the illumination of the DATA LINK light. The threat envelopes immediately appear on the TSD and within seconds the threat avoidance function has determined that in both cases the threat envelopes are penetrated by the nominal egress trajectory. Two additional navigation points are created and the trajectory generator re-computes a diversionary profile which threads the IFTC aircraft around the threats. This diversionary profile is drawn in dashed, predictive format as shown in Figure 3-22.

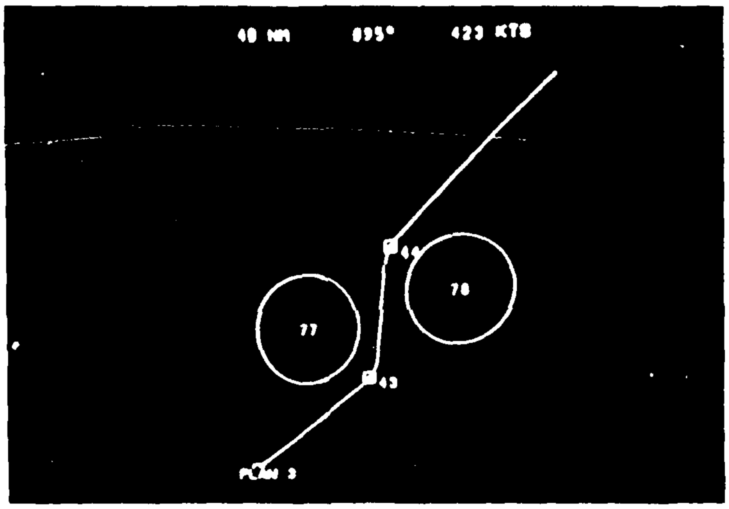
This profile is assigned a new plan number and the NAV SEL page is automatically placed on the status display with the cursor placed on the new plan number. At this point the pilot has been required to do nothing other than observe the TSD which displays enough information to allow the rapid assessment of the situation. If more threat information were available, the status display could be used to retrieve it; however, that step has not been mechanized in the simulator.

To engage the modified profile it is only necessary for the pilot to depress the ENGAGE key. The new profile is then engaged to the flight control system and the TSD is redrawn as shown in Figure 3-23. The entire process, from threat recognition to engagement of the modified profile, takes less than 15 seconds of pilot activity.

The remainder of the mission occurs without further incident. The climb out to the refuel tanker altitude begins just after WP66 and continues until tanker rendezvous on the friendly side of the FEBA.



NEW THREATS SUDDENLY APPEAR - TRAJECTORY IS
AUTOMATICALLY MODIFIED AND DISPLAYED ON TSD
FIGURE 3-22



THREAT AVOIDANCE PROFILE HAS BEEN ENGAGED
FIGURE 3-23

4 PILOT TESTING

4.1 PURPOSE/INTRODUCTION

The 4D IFTC system has the ability to respond to a changing tactical situation (as described by C^2 inputs and on-board sensors) by generating alternate, flyable trajectories which minimize the threat risk. These trajectories are presented graphically on a situation display and as alphanumeric information on a status display. The on-board trajectory generation capability has made possible the presentation of a higher level of information (the graphic representation of the newly generated trajectory) for pilot acceptance/rejection. Rapid assessment of, and response to, the presented information should increase pilot survivability and enhance mission success.

Typically, the pilot becomes familiar with the trajectory being flown through the preflight planning process; however, he has no familiarity with any trajectories generated by the IFTC system in response to the changing tactical environment. Since he is seeing it for the first time as it is presented on the displays, he must evaluate the situation and rapidly act to accept or reject the new profile.

Limited pilot testing of the IFTC system utilizing specially programmed laboratory displays in a fixed base simulator was accomplished during the final phase of the program. This test program was designed specifically to answer the following questions.

a. Does this capability (trajectory generation and mission related parameters)

   1. Assist the pilot by making the higher level of decision-making information available to him?

   2. Increase the pilot's ability to respond to a changing tactical environment, to C^2 redirects, to targets of opportunity?

   3. Increase the pilot's probability of mission success/survivability by increasing his awareness of threats and potential avenues of escape?

b. How should this capability be displayed to the pilot?

   1. Via existing instruments?

2. Is a HUD required?

3. Is a map display required?

4. Is a vertical profile display required; if so, what kind?

c. Can this capability be utilized to decrease the pilot's preflight planning requirements?

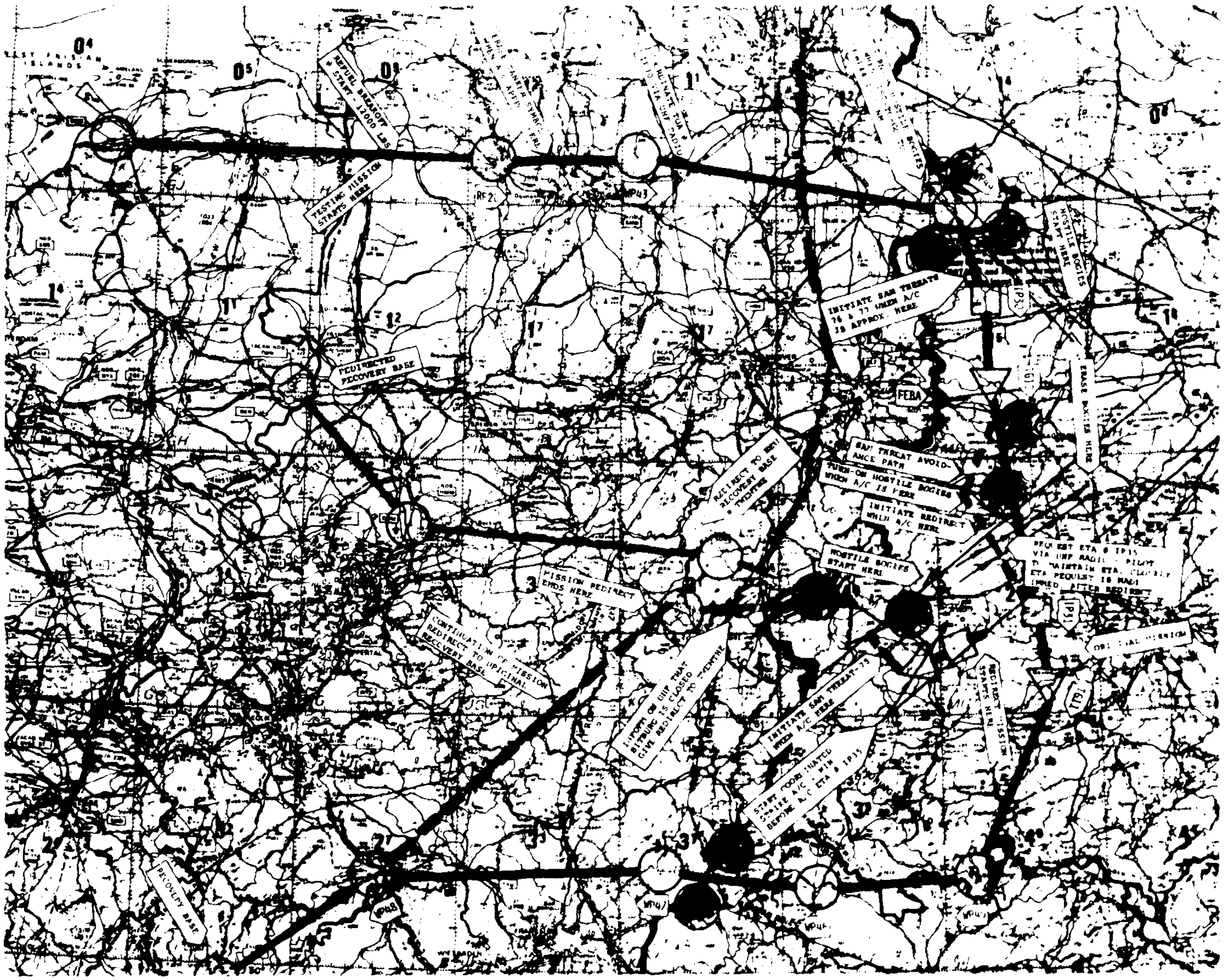
Several experimental designs were evaluated during the definition phase of pilot testing. Although complex comparative experiments were examined, the financial constraints of the program dictated that the experiments be kept relatively simple and that the quantity of subjects tested be small. It was determined that the selected test subjects should be familiar with advanced electronic display systems, with the combat environment, and have flown high performance fighter aircraft so that training activities could be minimized.

In summary, the decision was made to collect subjective data in the form of questionnaires.

4.2 THE MISSION

The experiment scenario was for a tactical fighter/bomber moving across a western Europe FEBA somewhere near the Fulda gap. He had a preplanned route involving completion of a refuel operation, crossing of the FEBA at low altitude, avoiding known SAM sites, making a coordinated air-to-ground weapon delivery on a target, moving to a second target, and returning across the FEBA at a specified time and route for egress.

During the mission he was given several unplanned deviations in the form of newly detected SAMs, unfriendly aircraft, a target redirect, and a landing redirect. His primary task was to complete the altered mission with its weapon deliveries without violating the SAM zones and to navigate the egress route. To do this he evaluated the information presented on the display system. Both the training mission and the test mission were very similar - only the route flown was different. Threats and redirects were introduced in different numbers and sequences. The testing profile is shown in Figure 4-1.



PILOT TESTING MISSION PROFILE
FIGURE 4-1

4.3 PILOT TRAINING

Pilot training was accomplished as follows:

a. Prior to his arrival in Grand Rapids each pilot was given a handbook (similar to that described in Sections 7.2 and 7.3) describing the cockpit equipment and its operation. It described the simulation system and the instruments that the pilot would be using during the testing.

b. Upon his arrival in Grand Rapids the subject pilot was given a classroom presentation discussing the capabilities of the system, and the pilot operations required to exercise each capability. Each pilot was given the opportunity for questions and answers during this presentation.

c. Each subject was then given "hands on" flight experience in the simulator. Each pilot was allowed several hours of actual simulator time to familiarize himself with the operation and capabilities of the system. Training flights were arranged to demonstrate the various system capabilities to be exercised during the experiments. An experimenter was available at the cockpit to answer any questions.

4.4 PILOT BRIEFING

Preflight and post-flight briefings were conducted with each experiment. These briefings were conducted in a conference room apart from the simulator site. During the preflight briefing, training aids consisting of maps and charts and the pilot's mission handbook were used to indicate the planned flight route and mission events. The preflight briefing was given just prior to the test flights. After each test run, the pilot was returned to the conference room for a debriefing with the experimenter. After the debriefing, each pilot was requested to fill out the post-experiment questionnaire.

4.4.1 Preflight Questionnaire

The preflight questionnaire, included in Appendix E, was designed to determine the following kinds of information.

Group A questions - Personal information relative to location, flight status and special training.

Group B questions - Degree of familiarity with advanced electronic display and information distribution systems.

Group C questions - Personal feelings with respect to time relevance in tactical missions and mission planning.

Group D questions - Preconceived notions about IFTC-like systems.

As indicated, the Group B questions were intended to provide insight into the subjects' familiarity with advanced displays and information systems. It was assumed that subjects familiar with these systems would not require as much training as those not familiar. Each subject indicated a familiarity with the systems in the Group B questions and all subjects responded to the training very rapidly.

Group C questions were directed primarily at time relevance, both in mission flight planning and in mission performance.

With Question 1 it was found that preflight planning involved a careful study of such items as the strike zone, anticipated threats, weather, weapon options, strike tactics, and anticipated fuel use. During the experiment, fuel use was underlined as an important element by each pilot's examination of the fuel estimates at the egress and refuel/recovery points, before acceptance of any redirects.

The answers to Question 2 indicated that a typical pilot spends at least as much time planning his mission as he does in executing it. This supports the hypothesis that he may find it difficult to accept newly generated trajectories with which he has had no planning familiarity, unless the cockpit displays can rapidly and adequately inform him of the new situation.

The answers to Questions 3 and 4 indicate that nuclear strikes are currently the most time-critical missions -- presumably because personal risk (flying through nuclear blast) is greatest.

The answers to the Group D questions indicate that this subject group had an awareness of IFTC concepts and a feeling that such a system would decrease workload in the tactical environment. None of the subjects expressed an unfavorable attitude toward the system. This was indicated by numerically averaging their answers to the last question of Group D. In this question, positive responses are ordered on the left of the matrix, opposing negative responses are ordered to the right of the matrix, and a neutral opinion is expressed by checking the box midway between the two responses. This question is repeated as Question 8 of the post-flight debriefing.

In general, all pilots expressed a high opinion of the IFTC concept prior to the test flights, and they did not change their opinion after the test flights. A numerical average of both preflight and post-flight responses falls between the first and second boxes on the extreme left of the matrix.

4.4.2 Post-Flight Questionnaire

The post-flight questionnaire is also included in Appendix E of this report. The following three areas of interest were addressed in the questionnaire:

a. How can the trajectory generation capability assist the pilot?

b. How should the trajectory generator information be displayed?

c. Can this capability reduce preflight planning time?

In addition, a fourth question group was included to provide the experimenters with insight on simulator realism/deficiencies.

d. How realistic was the mission/simulation?

The post-flight questions, grouped in these four categories, are listed in Table 4-1.

TABLE 4-I (1 of 2)
POST-FLIGHT QUESTIONNAIRE CATEGORIES

Group 1 Questions (How does trajectory generator assist?)

7, 8, 9, 10, 12, 13

Group 2 Questions (How should information be displayed?)

14, 15, 16, 17, 25, 26, 27, 28 - Display Interaction

TABLE 4-I (2 of 2)
POST-FLIGHT QUESTIONNAIRE CATEGORIES

18 - Flight Director Information

19 - Autopilot Coupling

20 - Command Altitude

21, 22, 23 - Map Display (TSD)

24 - Heads-Up Display

29, 30, 31 - Vertical Situation Display

Group 3 Questions (Can it reduce training time?)

5, 6, 11

Group 4 Questions (Simulator/mission realism, performance)

1, 2, 3, 4

The following paragraphs summarize the answers to the four question groups and integrate some of the pilot comments made during the debriefing.

Group 1 Questions

7. WHAT OPERATIONAL NEEDS DO YOU THINK A TRAJECTORY GENERATOR WILL SATISFY?

   A Greatly improve single pilot's ability to accurately navigate to target and absorb JTIDS inputs.

   B Allow estimates of track crossing points and anticipation of intercept points; also to determine intent of hostile aircraft.

   C Ability to reach target after A/A or A/G threat has gotten pilot off course; ability to react to redirect.

8. THE IFTC SYSTEM THAT COMPUTES FOUR-DIMENSIONAL PROFILES, PROVIDES PROFILE COMMAND AND ACCURATELY PREDICTS TIME OF

ARRIVAL (AT A WAYPOINT OR TARGET) IN RESPONSE TO CHANGING THREATS AND EVASIVE MANEUVERS WOULD REDUCE PILOT WORKLOAD IN TACTICAL SITUATIONS.

REQUIRED	A	C	B					UNNECESSARY
EASY	A	B,C						DIFFICULT
CLEAR	A	B,C						CONFUSING
HELP	A, B,C							HINDRANCE
SAFE	C	A,B						DANGEROUS
ACCEPTABLE	A, B,C							UNACCEPTABLE

9. DO YOU FEEL THAT A ONE-MAN CREW CAN HANDLE THE TACTICAL ENVIRONMENT WORKLOAD? A. Yes/B. Yes/C. No. EXPLAIN (I.E., WITH AUTOPILOT)

A Becomes more difficult with darkness, weather and mobile targets

B With proper training; pilot needs to be expert in hardware operation.

C Not with added systems and sensors projected for the near future.

10. DO YOU FEEL THAT THE IFTC SYSTEM WOULD IMPROVE MISSION TIME OF ARRIVAL ACCURACY?

significant improvement					no improvement
C	A				B

12. DO YOU FEEL THAT THE THREAT AVOIDANCE FEATURE IS BENEFICIAL?

significant benefit					no benefit
A C	B				

EXPLAIN:

A Yes, survival potential increases directly with situation awareness.

B I have no other way to learn of threats prior to entering the threat envelope.

C Yes, use of intel. info. drawn on maps and supplemented with RHAW, etc., just isn't accurate enough.

13. DO YOU FEEL THAT THE CAPTURE PROFILE FEATURE IS BENEFICIAL?

significant benefit					no benefit
C	A B				

A No comment.

B Must insure that a request for info on a capture point does not result in a plan change.

C The ability to get back on course after avoiding a threat is a must. Not too easy with current aircraft systems.

The Group 1 answers and comments point toward the ability of the IFTC system to generate a "return to plan" path (after diversion due to threats) as one of the biggest advantages to the pilot. Unplanned diversions can impose a severe navigation workload on the pilot. This capability reduces the "position relative to path" bookkeeping requirements and instantly provides updated information regarding time and fuel status at all future waypoints, as well as the steering information to return to the path.

Group 2 Questions

These questions fall into seven categories as indicated in Table 4-I. The first category addressed is display interaction. This relates primarily to the interaction between information presented on the TSD and status display. This interaction provides more pertinent data necessary for decision-making to the pilot. It is accomplished by programming the computer to integrate incoming threat information with existing position and planned trajectory data and to place the resulting new trajectory, if required, on the TSD and status display for the pilot's consideration and engagement.

The answers to this group of questions indicate that programmed interaction is a desirable feature. More work, however, must be accomplished to perfect the interaction sequence and the format of the information presented. As an example, it was found during debriefing that the subjects would likely have made an immediate accept/reject decision on the presented trajectory if fuel status at the refuel waypoint had been displayed automatically.

Programmed display interaction is a must in an IFTC type system. Its design, as with most control/display design, is an iterative process. Interactive display design activity must continue as the IFTC concept is further explored, expanded, and applied.

Group 2 Category 1 Questions

14. WHAT IS YOUR REACTION TO THE PROGRAMMED INTERACTION BETWEEN THE MODE SELECTION, THE STATUS DISPLAY, AND MAP DISPLAY?

    A Still not familiar enough with all the combinations to form a hard opinion.

    B Need simpler way to call up desired page; some info can be displayed on map display.

    C Logic is probably too complicated; too many switch actions required.

15. WOULD THIS FEATURE (THE PROGRAMMED INTERACTION) REDUCE PILOT WORKLOAD?

significant reduction						no reduction
B	A C					

16. RATE DIFFICULTY OF THE FOLLOWING:

    A. BUILDING AND INSERTING THE FLIGHT PLAN

simple	B					impossible
	A		C			

B. CHANGING THE FLIGHT PLAN

simple	B					impossible
	A	C				

C. OBTAINING PRESENT POSITION INFORMATION

simple						impossible
B/A/C						

D. DECIPHERING DATA LINK INFORMATION

simple						impossible
A	B		C			

<u>Group 2 Category 1 Questions</u> - continued

17. WAS THE INFORMATION SUPPLIED BY THE SPECIAL DATA PAGES INSUFFICIENT, SUFFICIENT OR EXCESSIVE?

WHAT INFORMATION WAS MISSING?

A Format could be improved; used in conjunction with moving map, item C. (above) would go right to the top of the effectiveness chart.

B Information excessive in some cases.

C Predicted gnd speed to go along with new predicted path. Could possibly set some minimum energy state within system so A/C would not slow too much. Keep the MACH up!

WHAT INFORMATION WAS EXCESSIVE?

A Difficult to comment intelligently at this point on the learning curve.

B Max-Min TOAs; other info with no data inserted.

C N/A

25. WHAT IMPROVEMENT/CHANGES WOULD YOU LIKE TO SEE?

A Improved format on data page; improved switchability.

B 1) simple access to information; 2) method of acknowledgement other than some action with info panel; 3) TOT & Fuel displayed on map during redirects.

C Add more functions to the system (TACAN, IFF, etc.)

26. WHAT WOULD YOU LIKE TO RETAIN (WITH OR WITHOUT MODIFICATIONS)?

A MAP CRT; some combination of the present data pages.

B Autoflight and autothrottle; debriefing capability - actually I would retain everything with minimal modification.

C All functions.

27. WOULD ANY ADDITIONAL DISPLAYS BE USEFUL?

A Moving map.

B No.

C No.

28. WOULD YOU LIKE TO REARRANGE THE INSTRUMENT PANEL LAYOUT?

A No, seems reasonable for intended tasks.

B No.

C No.

18. RATE THE DESIRABILITY OF THE FLIGHT DIRECTOR COMMANDS.

A Not sure if I would like raw deviation or flt. director commands.

B Essential.

C A must.

Flight director information pertaining to the planned trajectory was generally a benefit in the system.

Group 2 Category 3 Questions

19. WHAT FUNCTIONS DO YOU FEEL NEED TO BE COUPLED WITH THE AUTOPILOT?

    A Unsure.

    B Those coupled now are sufficient.

    C Just as they are.

    Coupling trajectory based command information to the autopilot, autothrottle is a desirable feature.

Group 2 Category 4 Questions

20. WERE THE ALTITUDE COMMANDS SUFFICIENT?

    A Yes.

    B Yes.

    C Yes.

    The vertical scale altimeter was modified for this experiment to provide a readout (both numeric and command bug) of instantaneous computer-generated command altitude. This capability was lacking in the earlier transport system and was found desirable in this system.

Group 2 Category 5

21. HOW READABLE WAS THE CRT MAP DISPLAY?

    A All right for the amount of info displayed.

    B Very easily read on 40 and 80 nm scale; decreasing clarity as scale increased.

    C Very good; Map scale increase/decrease functions are confusing; possibly should be re-named.

22. DO YOU FEEL THAT A PROJECTED MAP DISPLAY WOULD BE BENEFICIAL?

significant benefit						no benefit
A C	B					

23. WHAT IS YOUR FEELING ON A MAP DISPLAY?

required						not required
A C	B					

Map information is very important to the pilot. Projected map information would be useful if the map projection were the same format as the map used for preflight planning, to reinforce the pilot's familiarity with it.

Group 2 Category 6

24. DO YOU FEEL THAT A HUD IS NEEDED/REQUIRED?

required						not required
A,C,B						

EXPLAIN:

A Again situation awareness would go out of sight! All new fighters use Huds. Now would be a good time to start investigating the interface with IFTC.

B Allows head-up evaluation of the present head-down information. Allows visual search for hostile aircraft and targets.

C Increased technology adds more systems and sensors. Need all the help you can get, especially in Europe.

The interaction of HUD and IFTC information should be explored since pilots flying IFTC in a tactical situation will very likely be flying a HUD-equipped aircraft. The majority of flights will be "head up" and IFTC information must be integrated to be seen!

Group 2 Category 7

29. DO YOU FEEL THAT THE INFORMATION PRESENTED ON THE VSD MODE IS BENEFICIAL?

significant benefit						not required
	A	B C				

30. WHEN IS THE VSD MOST USEFUL?

A Short flight legs with large alt. Δs.

B I use it at turn points to (verify) vertical profile to next point.

C At low altitudes (TF), or near landing.

31. DO YOU HAVE A DESIRED FORMAT FOR THE VSD?

A Present looks good with some means of portraying local topography.

B No.

C As is.

Presentation of vertical (altitude/distance) profile information is important to a thorough understanding of the presented profile. The along-track distance/altitude VSD presentation is useful information and should be retained.

It would be desirable to investigate the further integration of the vertical and horizontal profile information (HSD and VSD modes) into a single multidimensional display.

Group 3 Questions

5. WHEN DID YOU FEEL COMFORTABLE WITH THE USE OF THE SYSTEM?

A Still not comfortable.

B Comfortable for testing mission; need few hours more training.

C All through the testing mission.

6. GIVE YOUR ESTIMATE OF ADDITIONAL TRAINING TIME THAT WOULD BE REQUIRED IF THIS SYSTEM WERE IMPLEMENTED IN A FIGHTER.

A Revised format and better switches would help more than additional training.

B 1 day ground school and 4-6 hours in the simulator.

C 1 to 2 weeks.

11. DO YOU FEEL THAT THE IFTC SYSTEM WOULD REDUCE MISSION PLANNING TIME?

significant reduction						significant increase
A,B			C			

EXPLAIN:

A Especially with DTM*.

B Yes, assuming that inputs were reliable, only would need to check map against plan for fuel est., TOT, etc.

C Probably not much change since the crew would still need to get intel., weather briefing and do preliminary flight planning.

IFTC is a complex system but carefully designed control/display interaction can both reduce the required pilot training time and increase the operational effectiveness.

Group 4 Questions

1. DID YOU FEEL THE SCENARIO PRESENTED WAS REALISTIC OF THOSE PROJECTED BY OPERATIONAL COMMANDS? WHAT WOULD MAKE IT MORE REALISTIC?

   A Yes.

   B Too many diverts; SAM redirects excellent; more info on Bogies.

   C Yes. Could increase threat density.

2. WHAT DID YOU NOTICE MOST DURING THE FLIGHT?

   A Too long to react to changes (more push-button training).

   B Absence of radio chatter; appearance of SAM sites.

   C Map presentation, threat dynamics and route flexibility.

*DATA TRANSFER MODULE - Device used for rapid loading of airborne computer - not implemented for this program.

3. WHICH DO YOU CONSIDER MOST IMPORTANT (CHECK ONE):

[xxx] MISSION ACCURACY

[ ] REDUCED WORKLOAD

[ ] OTHER (SPECIFY)

____

4. WHAT DID YOU USE AS A JUDGE OF PERFORMANCE OF THE SYSTEM?

   A I/F with the pilot.

   B Ability to retrieve information.

   C Ability to avoid threats, accept redirects and hit targets; probably could not have done in today's aircraft.

In general, the subjects felt the scenario presented was realistic. The equipment worked well during the simulation. The mission and equipment illustrated the capability and its use in a tactical environment.

5 FLIGHT PROFILE SYNTHESIS

5.1 FOUR-DIMENSIONAL TRAJECTORY GENERATOR

The IFTC concept is built upon using an on-board digital computer to generate a real-time, four-dimensional trajectory in space from inputs from the pilot or a data link. The basic requirements for the trajectory generator include the ability to,

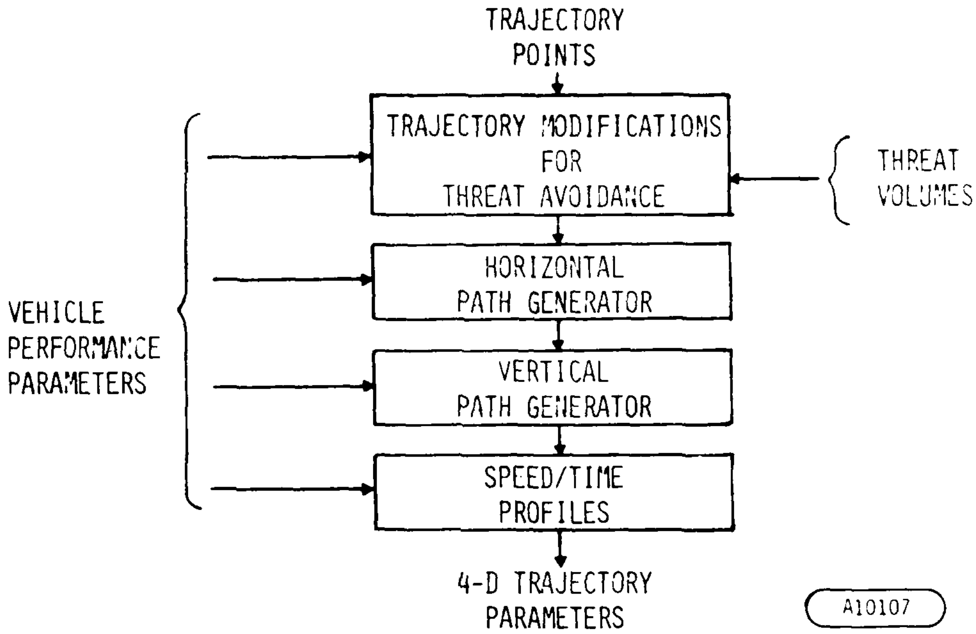
- Construct in real-time a curved three-dimensional path emanating from the aircraft and continuing through a specified series of points in space
- Use specified aircraft velocities and/or constraints to construct a flyable "speed/time" profile.

The 4-D trajectory generator consists of three primary parts. The first part is the horizontal path generator which uses constant radius turns and straight line segments in joining the aircraft and successive points in the mission profile. The second part consists of the vertical path generator which constructs constant flight path angles or spirals to change altitudes between profile points. The third part is the speed profile and time schedule generator which computes a flyable speed/time schedule for the mission profile. These basic blocks are shown in Figure 5-1. Integrated into the 4-D trajectory generator is a threat avoidance algorithm to determine the intersection of the 4-D profile and a defined lethal airspace volume. If a profile intersection occurs, new trajectory points are created or existing points are moved in order to establish a profile that avoids the threat volume.

5.1.1 Waypoint Parameters

The trajectory generator allows a greater flexibility for curved horizontal path and mission synthesis by allowing, but not requiring, many parameters at each waypoint to be specified. The minimum requirements for a waypoint are that the x, y, z position of the point be entered into the mission list, while a complete point definition may include the following parameters in addition to the required space coordinates:

- Time of Arrival
- Track Angle
- Airspeed
- Inbound or Outbound Flight Path Angle
- Wind Magnitude
- Wind Direction

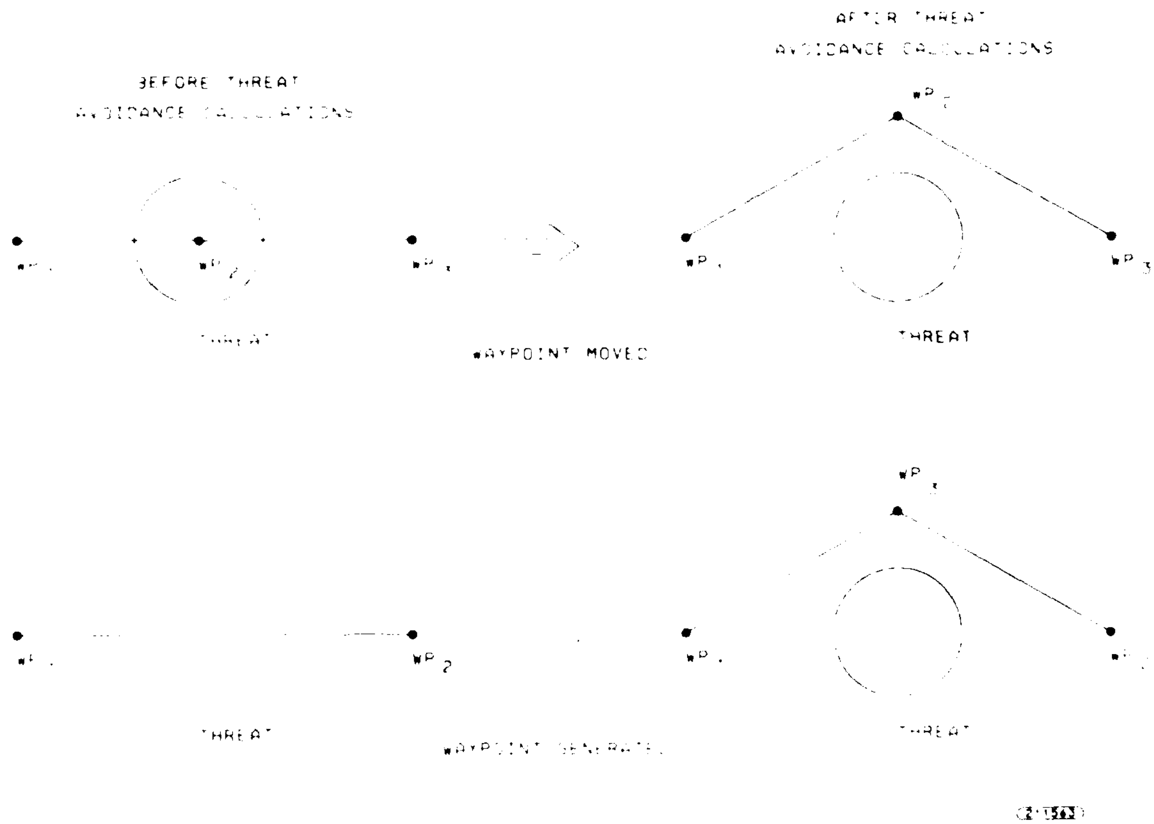


TRAJECTORY GENERATOR BLOCK DIAGRAM
FIGURE 5-1

In general, the use of the waypoint determines the number of parameters which are specified. For example, an ordinary waypoint may have only its position specified while a weapon delivery initial point (IP) may also have airspeed, track angle, and time-of-arrival specified.

5.1.2 Threat Avoidance

Threat avoidance algorithms have been integrated into the 4-D trajectory generation. For the IFTC study, the threat avoidance algorithm uses the known threat locations and determines those profile segments and waypoints which penetrate the lethal range envelopes. The avoidance algorithms will either move the location of a waypoint inside the avoidance area or add a waypoint to the mission plan which is outside of the avoidance area. See Figure 5-2 for avoidance examples.



THREAT AVOIDANCE EXAMPLES
FIGURE 5-2

5.1.3 Horizontal Path Generation

The horizontal path generator developed for the IFTC program determines the shortest path between two points in space. In general, if the points in question are not closer than four turn radii, the shortest flyable path between them consists of an initial turn, a straight segment and a final turn. This type of trajectory is computed only if the "to" waypoint has a specified ground track angle to be satisfied at the instant of flyover, as might be the case for a weapon delivery or rendezvous IP.

If the track angle is not specified, the computed trajectory will reduce to a simple turn followed by a straight segment toward the "to" waypoint. Waypoints without a specified track angle are used as general navigation points. The trajectory generator does not force "flyover" of these points, but will smoothly and predictably transition from an inbound track to an outbound track.

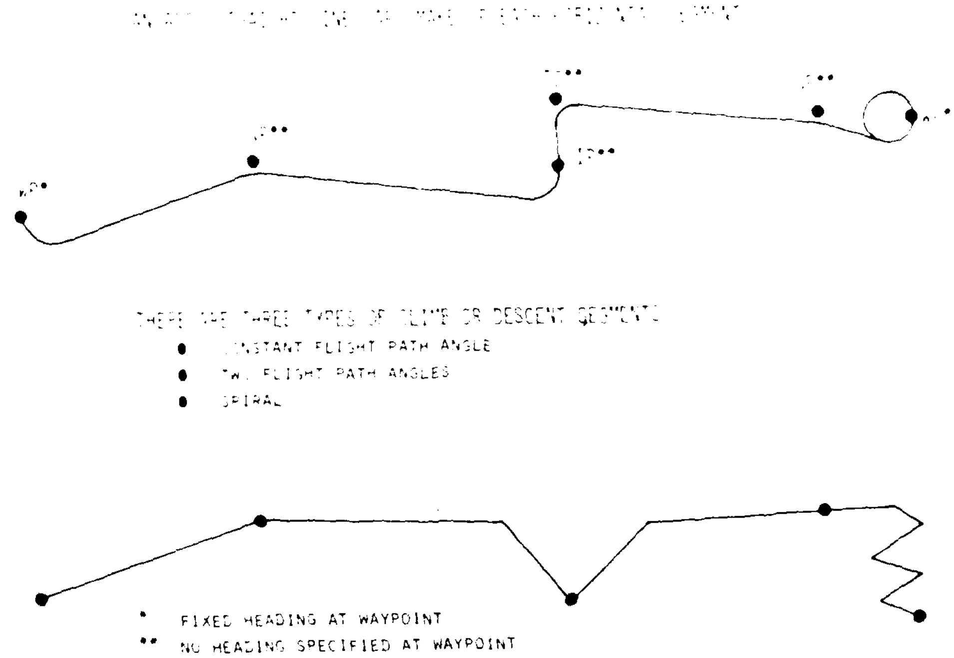
To determine the total mission profile the waypoints are processed by the trajectory algorithm in "from-to" pairs, starting with the aircraft as the first point, and continuing until the mission list is exhausted. Any changes to the mission which affect the trajectory result in immediate re-computing of the total profile. During the generation of the profile two basic types of waypoints are considered. These types are:

Waypoint Type	Description
1. Fixed Track ("Flyover")	The track angle over the waypoint is specified in that the aircraft will fly over the waypoint with a known track angle.
2. Round ("Non-Flyover")	The track angle at the waypoint is not specified. In this case the aircraft is not required to fly over the waypoint but only pass near it.

The above waypoint types will be referred to as Fixed and Round waypoints, respectively, in the discussion to follow.

In generating the horizontal portion of the 4-D profile it was assumed that each turn be made with a constant radius, and a constant airspeed. This assumption simplifies the curved portion of the horizontal trajectory generator but was found to complicate speed/time prediction calculations under certain conditions at the waypoints in that no aircraft acceleration was allowed during the turns. Instantaneous roll changes were assumed in the trajectory calculation, the effects of finite roll rates on time and distance calculations are negligible. Using these basic assumptions, the ground track generated by the trajectory generator is comprised of a series of turns and straight line segments tangent to the turns. The turns are found at or near the waypoints depending on the type of waypoint and the relative positions of the waypoints. See Figure 5-3.

The 4-D trajectory generator uses the GENT (trajectory generator) and TIMER (time/speed scheduler) subroutines to compute the mission profile parameters. (See Appendix C for



GROUND TRACK AND VERTICAL PROFILES
FIGURE 5-3

generalized flowchart of the GENT and TIMER subroutines.) The execution of the subroutines described below are controlled by the GENTEX subroutine (trajectory generator executive program). These subroutines may be considered as profile building blocks in the generation of the mission profile and are called from the GENT subroutine.

5.1.3.1 CS Subroutine (curved-straight)

This subroutine, CS, is used to generate the trajectory shown in Figure 5-4.

<u>INPUTS</u>

Parameters	Description
X_F, Y_F	Starting position (aircraft)
R	Radius of turn
X_T, Y_T	Fly-to point
ψ	Initial heading at X_F, Y_F

CURVED-STRAIGHT SEGMENT
FIGURE 5-4

Using the inputs listed above, this subroutine computes the ground-track parameters of the minimum length flight path between two given points.

The desired ground track consists of a circular turn followed by a straight line segment. Assuming the two waypoints are distinct, it is first necessary to determine the direction of the turn based on whether the second point lies to the right or left of the directed line that passes through the first point at a specified heading. When the direction of the turn is determined, the center of the turn is then computed. The direction of the turn is determined by:

$$H = \mathrm{PIMOD}(\pi/2-\psi)$$

$$\mathrm{SIGN} = \mathrm{SIGN}((Y_T-Y_F)\mathrm{COS}(H) - (X_T-X_F)\mathrm{SIN}(H)$$

where the SGN (·) function and the PIMOD (·) functions are shown in Figure 5-5. The turn center is determined by

$$X_C = X_F - R*SIGN*SIN(H)$$

$$Y_C = Y_F + R*SIGN*COS(H)$$

If it is determined that the fly-to-point is within the initial turn circle, an error flag is set and the subroutine is exited. If the waypoint placements are valid, it is then necessary to determine the angular extent of the turn, ψ_C. To determine ψ_C, it is first necessary to calculate α_1, α_2, S3, which are the heading of the line from the center of the turn to the first point, the heading of the line from the center of the turn to the second point, and the length of the straight line segment respectively.

$$\alpha_1 = PIMOD(H-SIGN\cdot\pi/2)$$

$$\alpha_2 = TAN^{-1}\left(\frac{Y_T-Y_C}{X_T-X_C}\right)$$

$$S3 = ((X_T-X_C)^2 + (Y_T-Y_C)^2 - R^2)^{\frac{1}{2}}$$

Using the variables computed above, the angular extent of the turn is:

$$\psi_C = \alpha_2 - \alpha_1 - SIGN \cdot \alpha_3$$

The length of the turn $S\phi$ is:

$$S\phi = |\psi_C|\cdot R$$

The ending point of the initial turn and the heading of the straight segment are:

$$\psi_S = PIMOD(H+\psi_C)$$

$$X_{TE} = X_C + R\cdot SIGN\cdot SIN(\psi_S)$$

$$Y_{TE} = Y_C - R\cdot SIGN\cdot COS(\psi_S)$$

STEP	PROCESS	NEXT STEP
1	$H = PIMOD(\pi/2 - \psi)$	2
2	SH = SIN(H), CH•COS(H)	3
3	DX = XT - XF, DY = YT - YF	4
4	IF $\|DX\| + \|DY\| = 0.0$	22*,5
5	SIGN = SGN(DY*CH - DX*SH)	6
6	SIGNR = SIGN*R	7
7	XC = XF - SIGNR * SH	8
8	YC = YF + SIGNR1 * CH	9
9	$D = (XT-XC)^2 + (YT-YC)^2 - R^2$	10
10	IF(D.LT.0)	28,11
11	S3 = SQRT(D)	12
13	$\alpha 1 = PIMOD(H - SIGN * \pi/2)$	14
14	$\alpha 2 = ATAN2(YT - YC, XT - XC)$	15
15	IF SIGN < 0	18,16
16	IF $\alpha 2 < \alpha 1$	17,20
17	$\alpha 2 = \alpha 2 + 2\pi$	20
18	IF $\alpha 2 > \alpha 1$	19,20
19	$\alpha 2 = \alpha 2 - 2\pi$	20
20	$\alpha 3 = ATAN(S3/R)$	21
21	$\psi_c = \alpha 2 - \alpha 1 - SIGN * \alpha 3$	23
22	$\psi_c = 0.0$	23

* T,F response to IF statement.

CS TABULAR FLOW CHART
FIGURE 5-5 (1 of 2)

STEP	PROCESS	NEXT STEP
23	$S\phi = R * \lvert\psi_c\rvert$	24
24	ψ_S = PIMOD$(H + \psi_c)$	25
25	$X_{TE} = X_c$ + SIGNR * SIN(ψ_S)	26
26	$Y_{TE} = Y_c$ - SIGNR * COS(ψ_S)	27
27	RETURN	
28	"WAYPOINTS TOO CLOSE"	29
29	RETURN	
	SGN(X) FUNCTION	
1	SGN = 1	2
2	IF(X) < 0	3,4
3	SGN = -1	4
4	RETURN	
	PIMOD(Y) FUNCTION	
1	PIMOD = Y	2
2	IF PIMOD = π	7,3
3	IF PIMOD > π	4,5
4	PIMOD = PIMOD - 2π	3
5	IF PIMOD $\leq -\pi$	6,7
6	PIMOD = PIMOD + 2π	5
7	RETURN	

CS TABULAR FLOW CHART
FIGURE 5-5 (2 of 2)

OUTPUTS

Parameters	Description
X_C, Y_C	Turn center
X_{TE}, Y_{TE}	End of turn
ψ_C	Angular extent of turn
$S\phi$	Length of turn
S3	Length of straight line
ψ_S	Heading of straight line

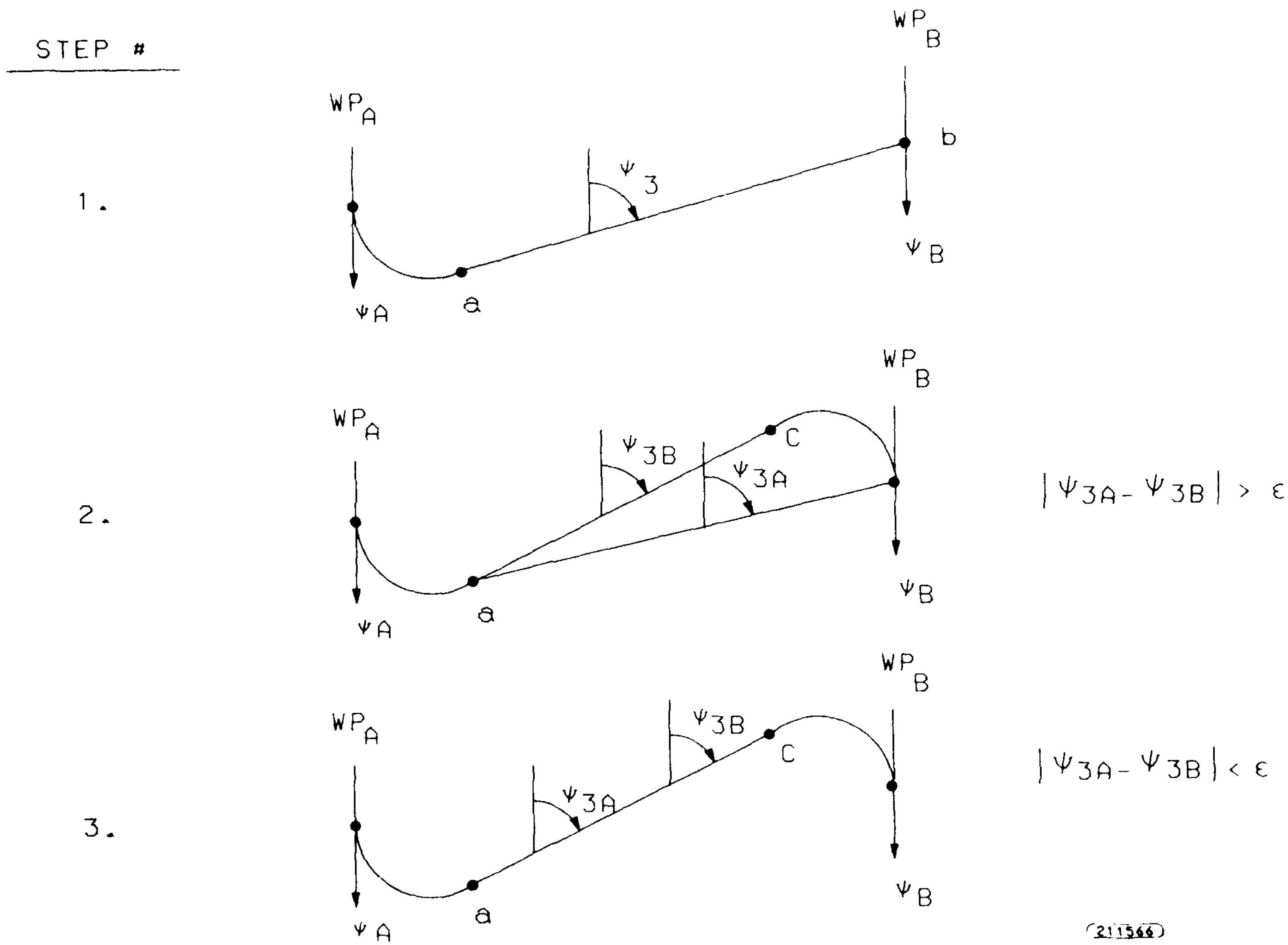
The CS subroutine solves the geometry problem that was shown in Figure 5-4 to obtain the outputs listed above. A tabular flow chart is shown in Figure 5-5 and a detailed flow chart in Figure C-4.

5.1.3.2 CSC Subroutine (curved-straight-curved)

The CSC subroutine determines the trajectory between two fixed waypoints by using the basic CS subroutine in an iterative algorithm. Figure 5-6 shows the that iterative CSC subroutine is finished when the angular difference between the two S3 segments is less than a specified value. The iterative trajectory algorithm is given below.

CSC Algorithm

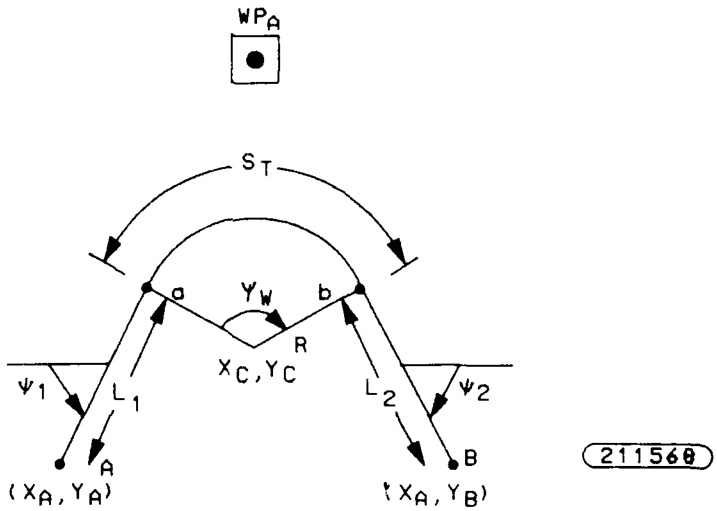
1. Use the CS subroutine to generate the trajectory from WP_A to WP_B. (See Step 1.)
2. Use the CS subroutine to generate the trajectory from WP_B to point a, where point a is the end of the curved path generated in Step 1.
3. Use the CS subroutine to generate the trajectory from WP_A to point c, where point c is the end of the turn generated in Step 2.
4. Check angular difference between ψ_{3A} and ψ_{3B}. If it is greater than a predetermined bound, go to Step 2, otherwise stop.



CSC PROFILE GENERATION SEQUENCE
FIGURE 5-6

5.1.3.3 RNDWP Subroutine

The final type of trajectory is generated by the subroutine, RNDWP, when a heading at the waypoint is not specified. Three points are required to effectively use the RNDWP subroutine. See Figure 5-7.



ROUND WAYPOINT TRAJECTORY
FIGURE 5-7

INPUTS

Parameters	Description
X_A, Y_A	Starting point position
X_B, Y_B	Ending point position
R	Turning radius
WP_{AX}, WP_{AY}	Waypoint position (Figure 5-8 and C-6)

Using the inputs listed above, the RNDWP subroutine is used to compute the ground track parameters of the flight path defined by three points.

To determine the necessary output data, the headings of the straight line segments are first determined:

$$\psi_1 = TAN^{-1} \left(\frac{WP_{AY}-Y_A}{WP_{AX}-X_A}\right)$$

$$\psi_2 = TAN^{-1} \left(\frac{Y_B-WP_{AY}}{X_B-WP_{AX}}\right)$$

STEP	PROCESS	NEXT STEP
1	$\psi_1 = ATAN2(WP_{AY}-Y_A,\ WP_{AX}-X_A)$	2
2	$\psi_2 = ATAN2(Y_E-WP_{AY},\ X_B-WP_{AX})$	3
3	$S1 = SIN(\psi_1),\ C1 = COS(\psi_1)$	4
4	$SIGN = SGN((Y_B-WP_{AY})*C1-(X_B-WP_{AX})*S1)$	5
5	IF SIGN LESS THAN 0.0	8,6
6	IF $\psi_2 < \psi_1$	7,10
7	$\psi_2 = \psi_2 + 2\pi$	10
8	IF $\psi_2 > \psi_1$	9,10
9	$\psi_2 = \psi_2 - 2\pi$	10
10	$\psi_W = \psi_2 - \psi_1$	11
11	$SIDE = R*TAN(\lvert\psi_W\rvert/2)$	12
12	$L1=((WP_{AX}-X_A)^2+(WP_{AY}-Y_A)^2)^{\frac{1}{2}}-SIDE$	13
13	IF L1 LESS THAN 0.0	20,14
14	$L2=((X_B-WP_{AX})^2+(Y_B-WP_{AY})^2)^{\frac{1}{2}}-SIDE$	
15	IF L2 LESS THAN 0.0	20,16
16	$S_T = R * \lvert\psi_W\rvert$	17
17	$X_a=WP_{AX}-SIDE*C1, Y_a=WP_{AY}-SIDE*S1$	18
18	$X_B=WP_{AX}-SIDE*COS(\psi_2)$, $Y_a=WP_{AY}-SIDE*SIN(\psi_2)$	19
19	RETURN	
20	"WAYPOINTS TOO CLOSE"	21
21	RETURN	

RNDWP TABULAR FLOW CHART
FIGURE 5-8

In addition, the magnitude and the direction of the turn is determined:

$$SIGN = SGN((Y_B - WP_{AY})COS\psi_2 - (X_B - WP_{AX})SIN\psi_2)$$

Based on the value of SIGN, the value of ψ_2 is compared to the value of ψ_1 and is either changed by $\pm 2\pi$ or is left unchanged. The angular extent of the turn is then determined:

$$\psi_W = \psi_2 - \psi_1$$

The arc length of the turn and the straight path segments are then determined by:

$$S_T = R^*|\psi_W|$$

$$S_M = R^*TAN(|\psi_W|/2)$$

$$L_1 = ((WP_{AX} - X_A)^2 + (WP_{AY} - Y_A)^2)^{1/2} - S_M$$

$$L_2 = ((X_B - WP_{AX})^2 + Y_B - WP_{AY})^2)^{1/2} - S_M$$

If either of the straight segment lengths are shorter than S_M, where S_M is the distance from WP_A to either a or b, an error flag is set and the program is exited.

The starting and ending points of the turn are determined:

$$X_a = WP_{AX} - S_M \sin\psi_1$$

$$Y_a = WP_{AY} - S_M \cos\psi_1$$

$$X_b = WP_{AX} + S_M \sin\psi_2$$

$$Y_b = WP_{AY} + S_M \cos\psi_2$$

OUTPUTS

a, b	Turn-straight segment tangent point
X_C, Y_C	Turn center
ψ_W	Angular extent of turn
ψ_1, ψ_2	Straight segment headings
S_T	Arc length of turn
L_1, L_2	Straight segment length

The RNDWP subroutine positions a prespecified turning radius tangent to the straight line segments A-WP_A and WP_A-B. It can be noted that as the angular separation between the line segments becomes smaller, the turn moves away from WP_A. If this separation becomes too great, a nominal heading is temporarily assigned to WP_A and the CSC subroutine is then used to generate the trajectory.

A sequence of calls are made to the RNDWP, CS, and CSC subroutines in the process of building a trajectory which starts at the aircraft and which is based on the headings specified at each waypoint. The subroutine GENT determines the necessary calling sequence required for each profile along with calculating the vertical profile and other parameters to be used by the speed/time algorithm.

5.1.4 Vertical Path Generation

For an altitude change between waypoints i and i +1, the vertical profile generator considers three types of vertical paths:

a. A constant vertical flight path angle (FPA) maintained between the two waypoints. (Indicated by "c" in Figure 5-9).

b. A two-segment trajectory consisting of a zero FPA segment and a segment having the specified FPA. (Indicated by "a" in Figure 5-9).

c. A spiral descent or ascent, whenever aerodynamic constraints or a pilot-inserted FPA eliminates the use of the first two types of vertical paths for achieving the altitude change. (Indicated by "b" in Figure 5-9).

VERTICAL PATH GENERATOR OUTPUTS
FIGURE 5-9

When unspecified, the FPA for the i^{th} profile segment is computed as

$$\gamma_i = \tan^{-1}((H_{i+1}-H_i)/i^{th} \text{ segment length})$$

For this type of altitude change, the aircraft flies the type "a" vertical profile listed above. When an FPA is specified, the profile generated -- either a two-segment or spiral profile -- depends on the value of the specified angle and the altitude differences between the "from" and "to" waypoints.

Assuming a two-segment profile is required, the profile generator determines where along the horizontal profile the start of an ascent or descent at the specified FPA will satisfy the specified altitude at the destination. (See Figure 5-9, line "a"). If the specified FPA is such that a spiral descent or ascent is required, the spiral is generated at the waypoint where the FPA is not specified. (See Figure 5-9, line "b"). It is assumed by the vertical trajectory generator that only one FPA can be specified between any two waypoints. In addition, the FPA constraints are calculated for each waypoint using the maximum available thrust, the predicted drag, the mass of the aircraft, and gravitational acceleration.

5.2 SPEED/TIME PREDICTION

The speed/time predictor algorithm (TIMER) developed for IFTC was designed to satisfy the speed and/or time-of-arrival (TOA) constraints as well as satisfy all aircraft and trajectory constraints associated with a waypoint(s) in a given flight plan.

The speed and/or TOA constraints problem is solved in two stages. The first stage positions acceleration segments between waypoints while the second stage modulates the intermediate velocity flown between waypoints. When the speed/time predictor algorithm is executed, each stage is applied to the flight trajectory generated by the 4-D trajectory generator in an effort to null TOA errors while satisfying the flight plan constraints. See Figure 5-10 for a general overview of the operation of TIMER.

The first stage of TIMER is considered as the acceleration positioning stage and is based on the ability to reposition the acceleration/deceleration segment found between the "from" and "to" waypoints. If the velocities at the waypoints are equal, this stage loses its ability to control the aircraft's TOA and is bypassed in the speed/time calculations.

To further clarify the operation of the first stage of the speed/time control algorithm, consider a "from-to" waypoint pair with specified velocities and TOAs at each point. If the TOA constraints are temporarily ignored, the aircraft could make a speed change at any number of points along the trajectory between the waypoints in order to satisfy the "to" waypoint arrival velocity. Figure 5-11 shows a possible velocity profile found between a "from-to" wayp[illegible] pair. The points p_1, p_2, p_3 are three possible poi[illegible] which acceleration (deceleration) could occur. [illegible] approaches the "from" waypoint the time required [illegible] "from-to" waypoint path decreases. Conversely, [illegible]

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FEASIBILITY STUDY FOR INTEGRATED FLIGHT TRAJECTORY CONTROL (FIG--ETC(U)
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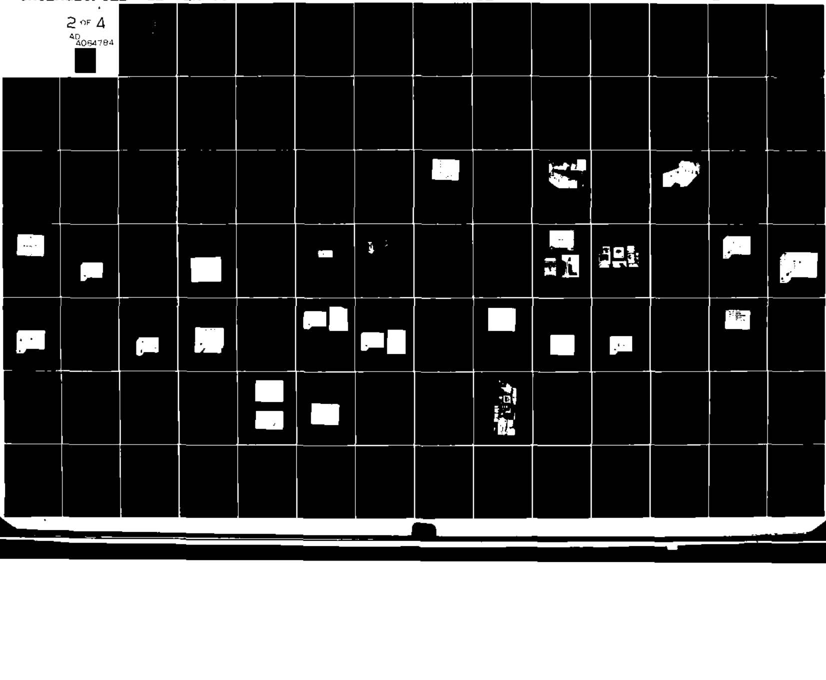
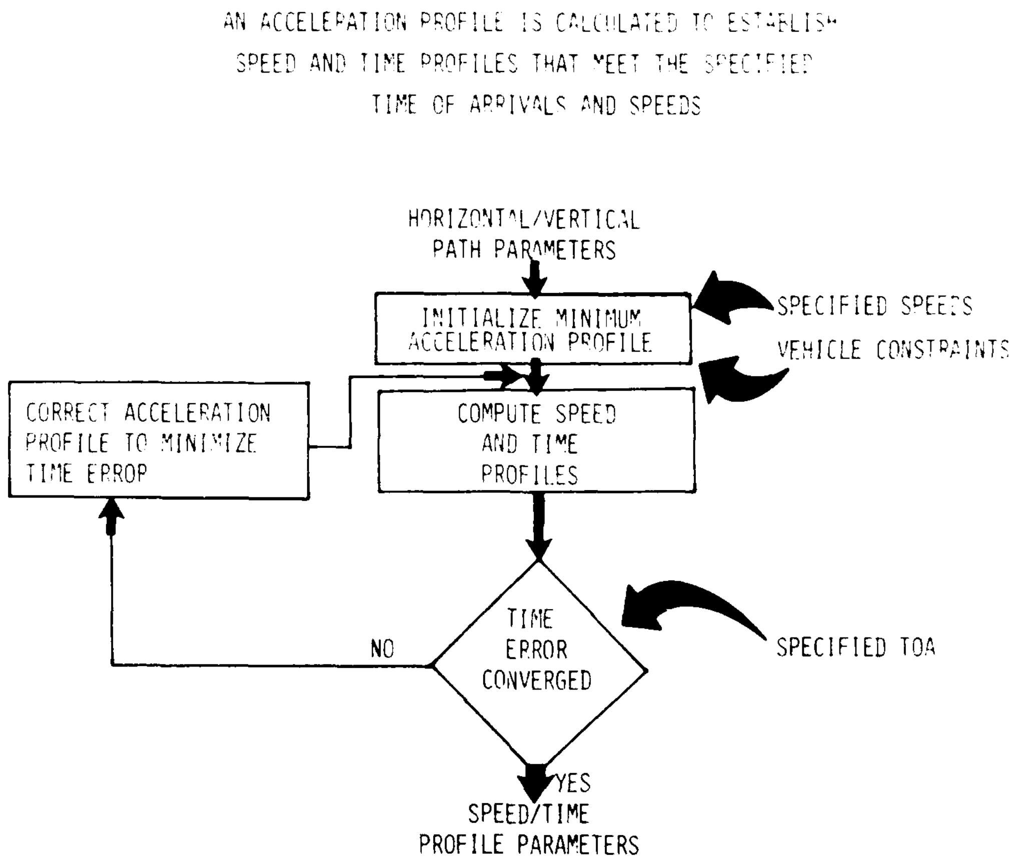
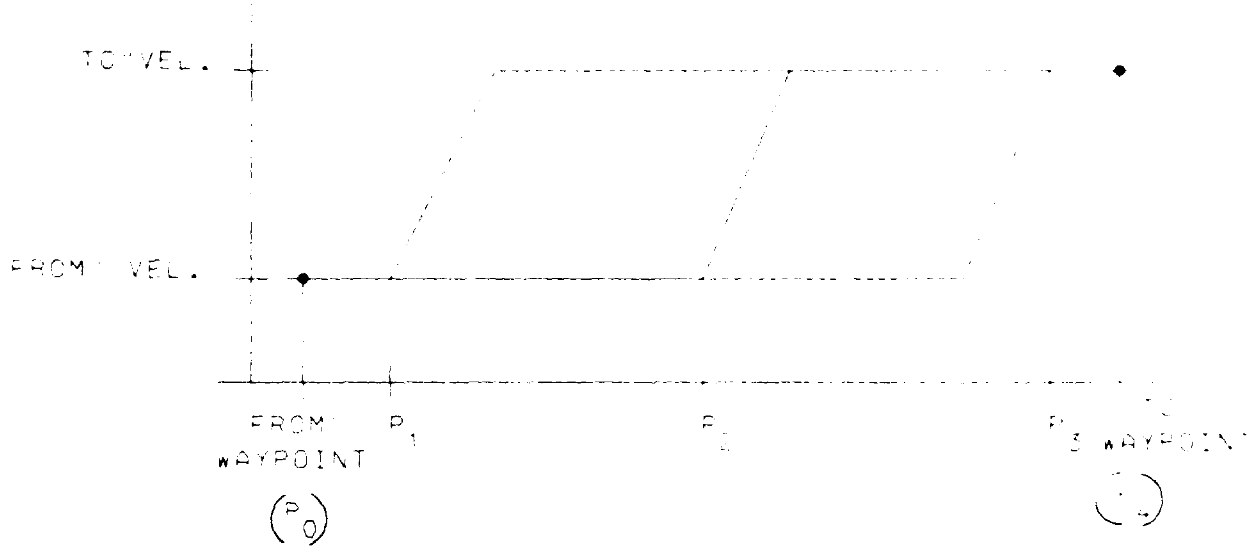




TIMER OPERATIONAL OVERVIEW
FIGURE 5-10

acceleration point p_2 approaches the "to" waypoint, the time required to fly the "from-to" waypoint path increases. The flight time changes which result from the movement of the acceleration segment is expressed by:

$$F_T = \frac{D - D_{VT} - D_A}{V_F} + \frac{D_{VT}}{V_T} + T_{ACC} \qquad (1)$$



ACCELERATION POSITIONING
FIGURE 5-11

simplifying (1)

$$F_T = T_{ACC} - \frac{D_A}{V_F} + \frac{D}{V_F} + D_{VT}\left(\frac{V_F - V_T}{V_F V_T}\right) \qquad (2)$$

where

F_T = total flight time for "from-to" path length of distance D (seconds)

T_{ACC} = time required to accelerate from F_V to V_T. This time is considered constant (seconds).

D_A = length of acceleration segment (feet).

V_F, V_T = required velocities at "from" and "to" waypoints, respectively (feet/sec).

D_{VT} = length of path between end of acceleration segment and "to" waypoint.

D = total length of "from-to" path as computed by trajectory generator.

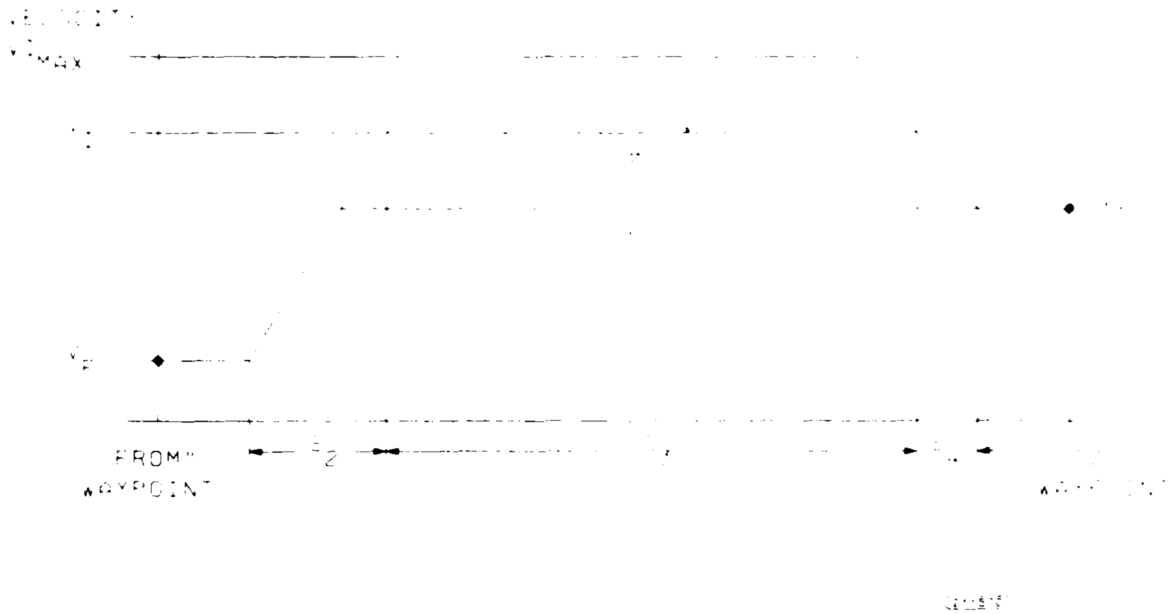
As can be seen in Equation 2 with the "from" and "to" waypoint velocities held constant and the acceleration terms held constant, the flight time, F_T, becomes proportional to the length of D_{VT}. In addition, as the differences in V_F and V_T increase, the amount of flight time "control" increases. It should be noted that if $V_F = V_T$, then this stage of the speed/time algorithm is bypassed for the "from-to" waypoint pair processing.

By knowing the velocity, acceleration, and path length parameters, the total amount of flight time which can be added to (subtracted from) a given trajectory can be determined. Therefore, knowing the desired TOA at a given waypoint and the current time, the actual aircraft TOA can be determined. If the actual TOA and desired TOA are not equal, adjustment of D_{VT} can be made to null the TOA error. The amount of flight time which can be added to (subtracted from) the total flight time is determined by the path length(s), aircraft acceleration, and waypoint velocity differences. Thus the amount of TOA error which can be removed is limited. When all acceleration positioning stage control has been expended and there still exists a time error, the speed/time algorithm will switch to the second stage of TOA control in a further attempt to null the TOA errors.

The second stage of the speed/time algorithm nulls TOA errors by adjusting the intermediate velocity (see figure 5-12). When this stage is entered, all stage one time control has been expended, leaving the acceleration (deceleration) segment either immediately following the "from" waypoint or just prior to the "to" point in the "from-to" pair. For the example shown in Figure 5-12, line "a" can be considered the starting point for the intermediate velocity speed change stage. If it is determined that the TOA is to be reduced further (have the aircraft arrive sooner at the waypoint), the intermediate velocity is moved to "b" with its max velocity being found at line "c".

The total time required to fly the "from-to" path having its velocity profile shown in Figure 5-12 "b" line is

$$T_T = \frac{S_3}{V_I} + \frac{V_I - V_F}{a_a} + \frac{V_I - V_T}{a_d}$$



INTERMEDIATE VELOCITY PROFILE
FIGURE 5-12

where

T_T = total flight time for the "from-to" path.

S_3 = length of intermediate velocity segment.

V_I = intermediate velocity.

V_F, V_T = specified "from-to" velocities, respectively.

a_a, a_d = aircraft acceleration and deceleration during velocity changes.

Therefore, since V_F, V_T, a_a, and a_d remain constant, the value of V_I can be varied to adjust T_T to null any remaining TOA errors.

The constraints placed on the velocity envelope shown in Figure 5-12 are determined prior to execution of the speed/ time algorithm. The constraints primarily involve velocity and acceleration limits as determined by the aircraft type and original 4-D profile as well as fuel load, weapon load, and environment. If the maximum/minimum velocity constraints are reached, TOA control stops and a TOA error will occur. This TOA error indicates that no further time adjustment can be made through changes in the intermediate velocity, and still operate within the a/c performance constraints and control law authority.

6 GUIDANCE AND CONTROL

6.1 GUIDANCE LAWS

The guidance laws are described in two sections. The first section describes the calculation of several reference variables which define the desired aircraft flight along the 4D profile. The second section defines the guidance errors which were used to steer the aircraft along the 4D trajectory.

6.1.1 Reference Aircraft Trajectory Parameters

The inputs needed to compute these reference trajectory parameters are provided by the trajectory generator. The trajectory generator stores these inputs in an array in memory that is indexed by a from-to-waypoint pair identifier. Several of these inputs apply to only certain portions of the waypoint pair horizontal trajectory segment. In particular, each waypoint pair segment may consist of up to seven subsegments which are defined in Table 6-I.

TABLE 6-I
SUBSEGMENT DEFINITIONS

Subsegment	Definition
1	Circular arc which connects the "from" waypoint to the start of a straight line segment.
2	Straight path distance flown with velocity specified for "from" waypoint.
3	Straight path distance to accelerate or decelerate to an intermediate velocity.
4	Straight path distance flown at a computed intermediate velocity.
5	Straight path distance to accelerate or decelerate to the velocity specified for the "to" waypoint.
6	Straight path distance flown with velocity specified for "to" waypoint.
7	Circular arc which connects the end of the straight path to the "to" waypoint.

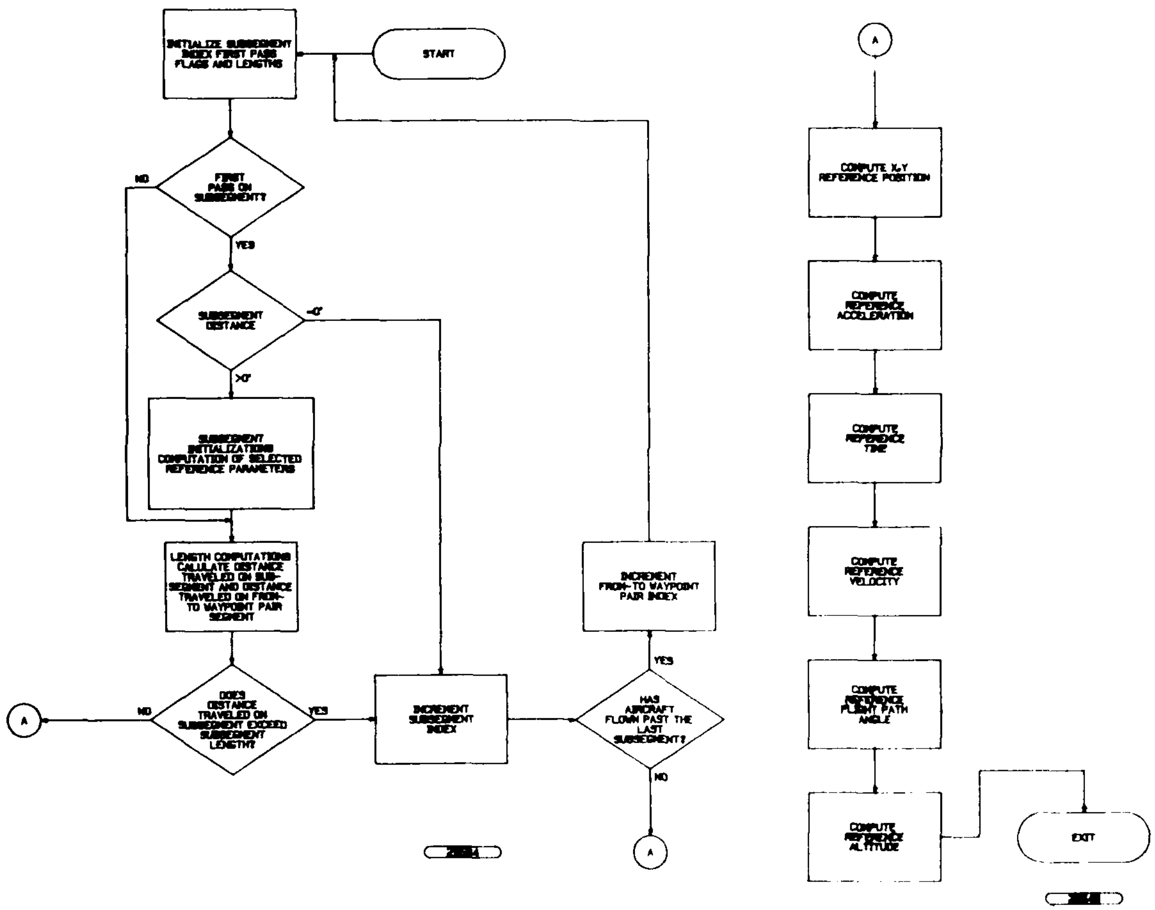
Summarizing, it is necessary for the guidance laws to compute a waypoint pair identifier index and a subsegment index in order to retrieve the desired inputs from computer memory.

A flow chart of the reference trajectory parameter calculations is shown in Figure 6-1. In this figure, an index is initially assigned a value of 1 to correspond to the first subsegment of a particular waypoint pair. On first pass, a set of parameters corresponding to a particular subsegment of the waypoint pair is computed. The guidance law determines whether a subsegment is defined for a particular waypoint pair by examining the subsegment distances computed by the trajectory generator. If a subsegment distance is equal to zero, that subsegment is not defined. In this case, the subsegment index is incremented and the next subsegment is examined. If a subsegment is defined, a set of parameters will be computed for use in subsequent computations. The distance the aircraft travels on the subsegment is calculated and compared with the length computed by the trajectory generator. When the computed distance exceeds the assigned length, the subsegment index is incremented and the next subsegment is examined. If this distance is not exceeded, the reference aircraft x, y coordinates, acceleration, time, velocity, flight path angle, and altitude are computed. When the aircraft has flown past the last subsegment, the waypoint pair index is incremented and the process repeats.

6.1.2 Subsegment Initializations

The reference trajectory parameters computed in the subsegment initialization include the reference velocity V_{ref}, the coordinates (x_{CTR}, y_{CTR}) of the center of the circular path being traversed, its radius R, type of turn, T, and a reference angle ψ_{ref} that defines the direction of the line segment connecting the center of the circle with the starting point of the turn. If we denote the subsegment index by I, we have

$$
\begin{aligned}
V_{ref} &= V_{FS} && \text{for} \quad I=1,2,3 \\
&= V_{IS} && I=4,5 \\
&= V_{TS} && I=6,7 \\
x_{CTR} &= x_{ITCTR} && I=1 \\
&= x_{FTCTR} && I=7 \\
y_{CTR} &= y_{ITCTR} && I=1 \\
&= y_{FTCTR} && I=7 \\
R &= R_{IT} && I=1 \\
&= R_{FT} && I=7
\end{aligned}
$$



REFERENCE TRAJECTORY PARAMETER CALCULATION
FIGURE 6-1

$$T = T_{IT} \qquad I=1$$
$$= T_{FT} \qquad I=7$$

$$\psi_{ref} = \tan^{-1}\left(\frac{x_{SPIT} - x_{CTR}}{y_{SPIT} - y_{CTR}}\right) \qquad I=1$$

$$= \tan^{-1}\left(\frac{x_{SPFT} - x_{CTR}}{y_{XPFT} - y_{CTR}}\right) \qquad I=7$$

where

V_{FS}: Airspeed specified at from waypoint

V_{IS}: Intermediate airspeed

V_{TS}: Airspeed specified at to waypoint

x_{ITCTR}, y_{ITCTR}: Coordinates of center of initial turn

x_{FTCTR}, y_{FTCTR}: Coordinates of center of final turn

R_{IT}: Radius of initial turn

R_{FT}: Radius of final turn

T_{IT}: Type of initial turn. $T_{IT} < 0$ indicates right hand turn and $T_{IT} \geq 0$ indicates left hand turn

T_{FT}: Type of final turn. $T_{FT} < 0$ indicates right hand turn and $T_{FT} \geq 0$ indicates left hand turn

x_{SPIT}, y_{SPIT}: Coordinates of starting point of initial turn

x_{SPFT}, y_{SPFT}: Coordinates of starting point of final turn

6.1.3 Length Computations

An incremental distance $\Delta ss(n)$ is computed every frame time that represents the along-track difference between the past aircraft reference position ($x_{ref}(n-1)$, $y_{ref}(n-1)$), and the point on the trajectory that defines the shortest distance between the present aircraft position ($x(n)$, $y(n)$) and the trajectory.

Defining the incremental along-track distance in this manner enables guidance errors to be defined so that the resulting control corrections will maintain minimal spatial errors. See Figure 6-2.

For $2 \leq I \leq 6$ (straight paths)

$$\Delta ss(n) = (x(n) - x_{ref}(n-1))*\sin\psi_c + (y(n) - y_{ref}(n-1))*\cos\psi_c$$

where ψ_C: straight segment heading

For $I = 1$, $I = 7$ (curved paths)

$$\psi_{TEMP} = \tan^{-1}[(x(n)-x_{CTR})/(y(n) - y_{CTR})]$$

$$\begin{aligned} \psi_{A/C}(n) &= \psi_{TEMP} & \psi_{TEMP} \geq 0 \\ &= \psi_{TEMP} + 2\pi & \psi_{TEMP} < 0 \end{aligned}$$

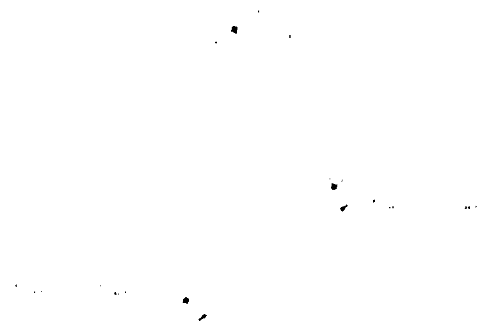
$$\begin{aligned} \Delta\psi &= \psi_{A/C}(n) - \psi_{ref}(n) &, T < 0,\ \psi_{A/C}(n) \geq \psi_{ref}(n) \\ &= \psi_{A/C}(n) - \psi_{ref}(n) + 2\pi &, T < 0,\ \psi_{A/C}(n) < \psi_{ref}(n) \\ &= -(\psi_{A/C}(n) - \psi_{ref}(n)) + 2\pi &, T \geq 0,\ \psi_{A/C}(n) > \psi_{ref}(n) \\ &= -(\psi_{A/C}(n) - \psi_{ref}(n)) &, T \geq 0,\ \psi_{A/C}(n) \leq \psi_{ref}(n) \end{aligned}$$

$$\Delta ss(n) = R \cdot \Delta\psi$$

In addition to the incremental along-track distance, the distance traveled on the present subsegment ($ss(n)$) and the distance traveled on the from-to waypoint pair path segment ($s(n)$) is computed.

$$ss(n) = ss(n-1) + \Delta ss(n)$$

$$s(n) = s(n-1) + \Delta ss(n)$$



STRAIGHT PATHS

CURVED PATHS

REFERENCE POSITION
FIGURE 6-2

6.1.4 x,y Reference Position

For circular paths, the reference position is computed by a polar to rectangular coordinate conversion. The vector originating at the center of the circle with magnitude equivalent to the radius and with the same direction as the line segment connecting the *current aircraft* position with the circle center, is resolved along the x and y axes.

We have

for I = 1, I = 6 (curved path subsegments)

$$\psi_{ref}(n) = \psi_{A/C}(n)$$
$$x_{ref}(n) = x_{CTR} + R\sin(\psi_{ref}(n))$$
$$y_{ref}(n) = y_{CTR} + R\cos(\psi_{ref}(n))$$

The reference position for straight paths is computed in two steps. The first step is to compute the ratio of the distance traveled on the straight segment to the total length of that segment. The reference position is computed by multiplying this ratio by the difference between the starting point and the end point coordinates of the straight line segment and then adding the result to the starting point. *We have for straight path subsegments* ($2 \le I \le 6$)

$$SF = (s(n) - s_1)/s_{ST}$$
$$x_{ref}(n) = x_{EPIT} + (x_{SPFT} - x_{EPIT})SF$$
$$y_{ref}(n) = y_{EPIT} + (y_{SPFT} - y_{EPIT})SF$$

where

s_1: Length of subsegment 1

(x_{EPIT}, y_{EPIT}): Coordinates of end point of initial turn

(x_{SPFT}, y_{SPFT}): Coordinates of starting point of final turn

s_{ST}: Length of straight line portion of waypoint pair trajectory

6.1.5 Acceleration Reference

The guidance law determines which one of four reference acceleration values computed by the trajectory generator for each waypoint pair are to be used. Accelerations or decelerations take place in subsegments 3 and/or 5. Two reference accelerations are defined per subsegment as different accelerations are needed if a flight path angle change occurs within that subsegment. In addition to determining which one of the four accelerations is appropriate, the guidance law determines whether they are accelerations or decelerations by comparing the intermediate with the specified "from" point and "to" point velocities.

$$
\begin{aligned}
a_{ref} &= a_{21} && I = 3,\ s(n) \le s_{\Delta\gamma},\ V_{FS} \le V_{IS} \\
&= -a_{21} && I = 3,\ s(n) \le s_{\Delta\gamma},\ V_{FS} > V_{IS} \\
&= a_{22} && I = 3,\ s(n) > s_{\Delta\gamma},\ V_{FS} \le V_{IS} \\
&= -a_{22} && I = 3,\ s(n) > s_{\Delta\gamma},\ V_{FS} > V_{IS}
\end{aligned}
$$

$$
\begin{aligned}
a_{ref} &= a_{41} && I = 5,\ s(n) \le s_{\Delta\gamma},\ V_{TS} > V_{IS} \\
&= -a_{41} && I = 5,\ s(n) \le s_{\Delta\gamma},\ V_{TS} \le V_{IS} \\
&= a_{42} && I = 5,\ s(n) > s_{\Delta\gamma},\ V_{TS} > V_{IS} \\
&= -a_{42} && I = 5,\ s(n) > s_{\Delta\gamma},\ V_{TS} \le V_{IS}
\end{aligned}
$$

where:

a_{21}: Acceleration on subsegment 3 prior to flight path angle change

a_{22}: Acceleration on subsegment 3 after flight path angle change

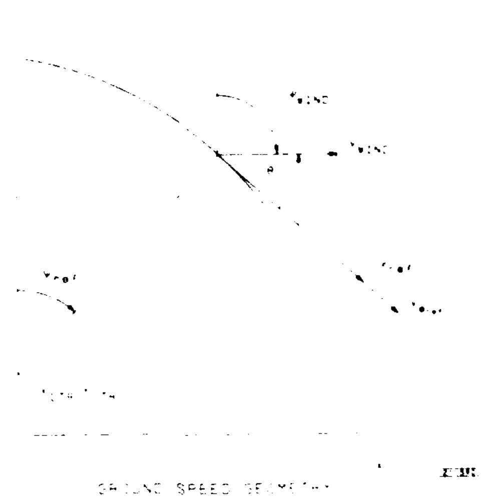
a_{41}: Acceleration on subsegment 5 prior to flight path angle change

a_{42}: Acceleration on subsegment 5 after flight path angle change

$s_{\Delta\gamma}$: Distance from "from" waypoint to change in flight path angle

6.1.6 Time Reference

The time the aircraft should be at the reference position is computed from the knowledge of the incremental along-track distance, the acceleration reference, and a ground speed reference. The ground speed reference is computed by adding the wind and true airspeed vectors together as shown in Figure 6-3. The time to fly the incremental distance $\Delta ss(n)$ is computed and added to the previous reference time to obtain the present reference time.



GROUND SPEED GEOMETRY
FIGURE 6-3

The incremental time calculation is dependent on whether the subsegment contains accelerations.

For curved subsegments (I = 1,7)

$$\theta = \psi_{WIND} - \psi_{ref}(n) - \pi/2 \qquad T < 0$$

$$\quad = \psi_{WIND} - \psi_{ref}(n) + \pi/2 \qquad T \geq 0$$

$$V_{g_{ref}} = V_{ref} + V_{WIND}\cos\theta$$

For subsegments with no accelerations (I = 1,2,4,6,7)

$$\Delta t = \Delta ss(n)/V_{g_{ref}}$$

For subsegments with accelerations or decelerations (I = 3,5)

$$\Delta t = \frac{-V_{g_{ref}}}{|a_{ref}|} + \left[\frac{2 \cdot \Delta ss(n)}{|a_{ref}|} + \left(\frac{V_{g_{ref}}}{|a_{ref}|} \right)^2 \right]^{1/2}$$

$$t_{ref}(n) = t_{ref}(n-1) + \Delta t$$

where

ψ_{WIND}: Wind direction

V_{WIND}: Nominal wind magnitude

Vg_{ref}: Ground speed reference

$\Delta t(n)$: Time to fly $\Delta ss(n)$

t_{ref}: Reference time

6.1.7 Velocity Reference

The trajectory generator defines three different reference velocities between waypoints - a velocity at the "from" waypoint (V_{FS}), an intermediate velocity (V_{IS}), and a velocity at the "to" waypoint. Velocity changes are made by applying a constant acceleration or deceleration (a_{ref}). For these cases, the reference velocity (V_{ref}) is computed using the relationship

$$V_{ref}(n) = V_{ref}(n-1) + a_{ref}\,\Delta t(n)$$

6.1.8 Flight Path Angle Reference

For each waypoint pair the trajectory generator defines an inbound flight path angle (γ_{IB}), an outbound flight path angle (γ_{OB}), and the distance from the "from" waypoint to the flight path angle change ($s_{\Delta\gamma}$). The reference flight path angle (γ_{ref}) is computed from these quantities using the relations

$$\begin{aligned} \gamma_{ref} &= \gamma_{IB} \qquad & s(n) < s_{\Delta\gamma} \\ &= \gamma_{OB} \qquad & s(n) \geq s_{\Delta\gamma} \end{aligned}$$

6.1.9 Altitude Reference

The reference altitude is computed in one of two ways depending on the relative location of the reference position to the point on the trajectory where the flight path angle changes.

This yields

$$
\begin{aligned}
z_{ref} &= z_{SPIT} + s(n)\tan\gamma_{ref} & s(n) \leq s_{\Delta\gamma} \\
&= z_{EPFT} - s_{TOTAL}\tan\gamma_{ref} & s(n) > s_{\Delta\gamma}
\end{aligned}
$$

where

z_{ref}: Reference altitude

z_{SPIT}: Altitude of starting point of initial turn

z_{EPFT}: Altitude of end point of final turn

s_{TOTAL}: Length between waypoints

6.2 GUIDANCE CONTROL LAWS

6.2.1 Guidance Feedback Errors

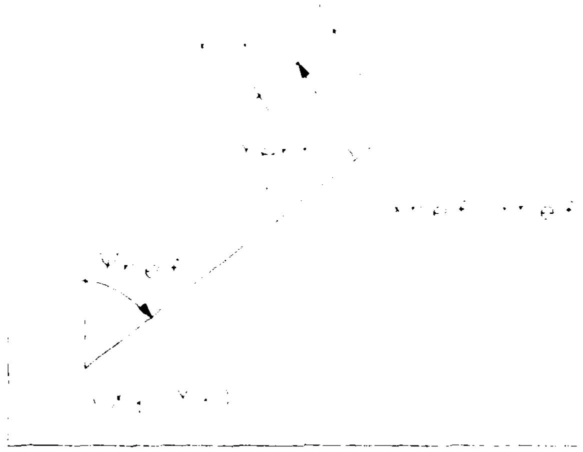
Rate and displacement errors are computed for all three axes in order to null path errors and provide path damping.

6.2.1.1 Horizontal Guidance

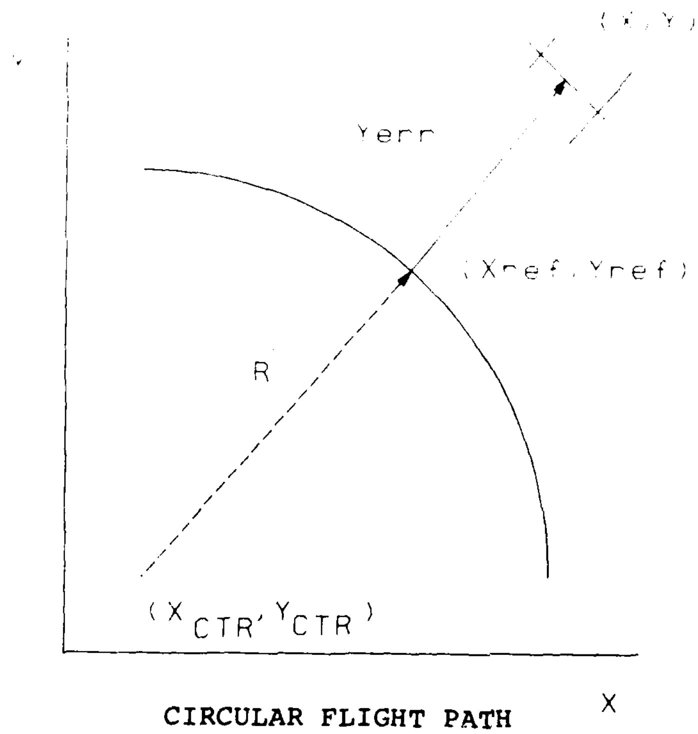
The horizontal trajectory consists of straight line and circular arc segments. Cross-track and cross-track rate errors are defined to provide displacement and rate terms for steering the aircraft along a computed horizontal path. In addition, a nominal bank angle is computed to define the roll attitude necessary to fly a steady-state turn of constant radius and ground speed. The horizontal plane geometry defining the cross-track errors is shown in Figure 6-4.

For straight line paths ($2 \leq I \leq 6$)

$$y_{err} = (y - y_{ref})\sin\psi_{ref} - (x - x_{ref})\cos\psi_{ref}$$



STRAIGHT FLIGHT PATH



CIRCULAR FLIGHT PATH

HORIZONTAL GUIDANCE ERRORS
FIGURE 6-4

For curved paths (I = 1,7)

$$y_{err} = \left(\sqrt{(x_{CTR} - x)^2 + (y_{CTR} - y)^2} - R\right) \quad T < 0$$

$$= \left(\sqrt{(x_{CTR} - x)^2 + (y_{CTR} - y)^2} - R\right) \quad T \geq 0$$

The cross-track rate errors are computed by differentiating Y_{err} with respect to time. Thus, for straight line paths ($2 \leq I \leq 6$)

$$\dot{y}_{err} = -V_N \sin\psi_{ref} + V_E \cos\psi_{ref}$$

where V_N and V_E are the north and east components of velocity, respectively.

For curved paths (I = 1,7)

$$\dot{y}_{err} = \left[\frac{(x_{CTR} - x)V_E + (y_{CTR} - y)V_N}{\sqrt{(x_{CTR} - x)^2 + (y_{CTR} - y)^2}}\right] \quad T < 0$$

$$= -\left[\frac{(x_{CTR} - x)V_E + (y_{CTR} - y)V_N}{\sqrt{(x_{ctr} - x)^2 + (y_{CTR} - y)^2}}\right] \quad T \geq 0$$

The nominal bank angle for steady-state turns of constant radius and ground speed is defined by

$$\phi_{ref} = \tan^{-1} \frac{V_g^2}{gR}$$

where V_g is ground speed and g is the acceleration of gravity constant. The bank angle error is then the difference between the nominal bank angle and the aircraft bank angle ϕ, i.e.,

$$\phi_{err} = \phi - \phi_{ref}$$

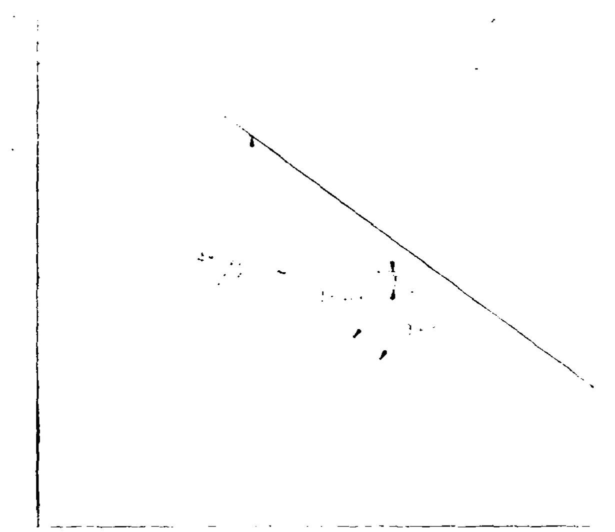
6.2.1.2 Vertical Guidance

Altitude and flight path angle errors are defined to provide displacement and rate terms for steering the aircraft along the computed vertical path. Altitude and flight path angle errors are defined in the vertical plane geometry shown in Figure 6-5. as

$$z_{err} = z - z_{ref}$$

and

$$\gamma_{err} = \gamma - \gamma_{ref}$$



VERTICAL PLANE GEOMETRY
FIGURE 6-5

6.2.1.3 Longitudinal Guidance

Time and velocity errors are defined to provide displacement and rate terms for steering the aircraft along track. The time error is the difference between the present time and the reference time. The velocity error is the difference between the aircraft ground speed and the reference ground speed, i.e.,

$$t_{err} = t - t_{ref}$$

and

$$V_{err} = V_T \cos\gamma - V_{ref}$$

In addition, a reference acceleration is computed that defines velocity changes along the 4D trajectory. The acceleration error $a_{err} = a - a_{ref}$.

6.2.2 Crossfeed Terms

Crossfeed terms were added to minimize loss of altitude during turns and speed changes resulting from changes in pitch attitude. These crossfeed terms were mechanized by providing an additional pitch command (θ_{LIFT}) during turns according to the equation

$$\theta_{LIFT} = K_{LIFT} \cdot \frac{(1 - \cos\phi)}{\cos\phi}$$

and a throttle command term $T_{W.O.}$ which senses pitch changes by washing out pitch attitude (θ) according to the relation

$$T_{W.O.} = K_{W.O.} \cdot \left(\frac{s}{s + \frac{1}{\tau_{WO}}} \right) \theta .$$

6.2.3 Open Loop Terms

Open loop controls are employed to keep the feedback control errors small during periods of transition in aircraft attitude. For example, when the aircraft is transitioning from straight to curved flight, the reference bank angle ϕ_{ref} displays a jump discontinuity. Similarly, a discontinuity exists when the reference flight path angle γ_{ref} changes. These discontinuities are undesirable as they introduce transients into the feedback controls. Open loop controls were designed to smooth these discontinuities and provide better path following. Smoother transition between straight and curved flight was implemented by filtering the reference bank angle, i.e.,

$$\phi_{ref} = \frac{\phi_{ref}}{s + \frac{1}{\tau}}$$

Improved tracking was obtained by introducing the new ϕ_{ref} prior to the horizontal path change. Switching was performed when the aircraft was within two seconds of the point on the trajectory where the roll attitude transition occurs.

Smoother transition between flight path angle changes was accomplished by switching in the new flight path angle when the pitch maneuver would result in a normal acceleration of 2.25 ft/sec^2. Normal acceleration

$$N_z = \frac{\frac{V^2}{g}}{R} = 2.25 \text{ ft/sec.}$$

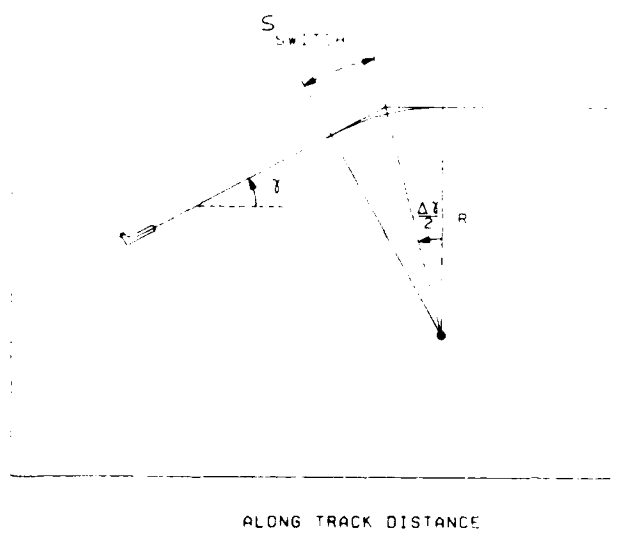
Referring to Figure 6-6, $R = \frac{2}{\Delta\gamma} S_{SWITCH}$.

Substituting R in the N_Z equation and solving for S_{SWITCH} we have,

$$S_{SWITCH} = \frac{\frac{V^2}{g}|\Delta\gamma|}{2(2.25)}$$

Flight path angle switching occurs when the distance between the reference position on the trajectory and the point at which the flight path angle change occurs, is less than s_{SWITCH}. Actual implementation of the switching logic is given by

$$(s(n) - s_{\Delta\gamma}) < s_{SWITCH}.$$



VERTICAL CAPTURE
FIGURE 6-6

6.2.4 Throttle Activity

In the early stages of the IFTC program, considerable difficulty was encountered in obtaining a satisfactory longitudinal control system without excessive throttle activity. The throttle activity was eventually reduced to acceptable limits by computing a nominal throttle position which would provide the thrust necessary to reach an airspeed close to the reference airspeed computed by the guidance laws. The longitudinal feedback controls effectively correct for any nominal throttle error. The nominal throttle position computation was implemented by first computing the nominal thrust necessary to achieve a desired airspeed. Using a point mass model

$$T = D + W\sin\gamma_{ref} \qquad \text{Eq. 6-1}$$

where

T = thrust

W = weight

$$D = -QSC_D = -\left[\frac{1}{2}\rho(z_{ref})V_{ref}^2\right]SC_{X_S}$$

and

ρ = air density

S = wing reference area

C_{X_S} = dimensionless drag

γ_{ref}, z_{ref} and V_{ref} are computed by the guidance laws. C_{X_S} is computed from table data stored in computer memory. Thrust as a function of throttle position δt is given by

$$T = [700 + (179 - M1)\cdot\delta_t] \cdot HP \qquad 0 \le \delta_t \le 50\% \qquad \text{Eq. 6-2}$$

$$= [9650. - 2250.\cdot Mach + (137. + M1)\cdot(\delta_t - 50.)]\cdot HP \qquad 50\% < \delta_t \le 100\%$$

where

$HP = 1 - .00001538 \cdot z$

$M1 = 45. \cdot MACH$

Combining Equations 6-1 and 6-2 and solving for the nominal throttle position

$$\delta_{t_{nom}} = \frac{T - 700 \cdot HP}{(179 - M1) \cdot HP} \qquad \delta_{t_{nom}} \leq 50\% \qquad \text{Eq. 6-3}$$

$$= \frac{\left(\frac{T}{HP}\right) - 9650. + 2250. \cdot MACH}{1.37 + M1} + 50. \qquad \delta_{t_{nom}} > 50\%$$

It is possible that Equation 6-3 could return a value of $\delta_{t_{nom}}$ >100% or $\delta_{t_{nom}}$ <0%. Therefore, the nominal throttle command is limited such that 0% $\leq \delta_{t_{nom}} \leq$ 100%. The sum of the feedback terms is limited to ± 20% to ensure minimal throttle activity while still allowing for correction of errors in the nominal throttle computation.

6.2.5 Control Law Equations

The guidance errors, crossfeed terms, and open loop terms were used to steer the aircraft along the 4D trajectory. These control laws are shown in block diagram form in Figures 6-7, 6-8, and 6-9. Lateral path steering was achieved by computing a roll attitude command and applying it to the lateral SAS yielding an aileron deflection. This command is given by

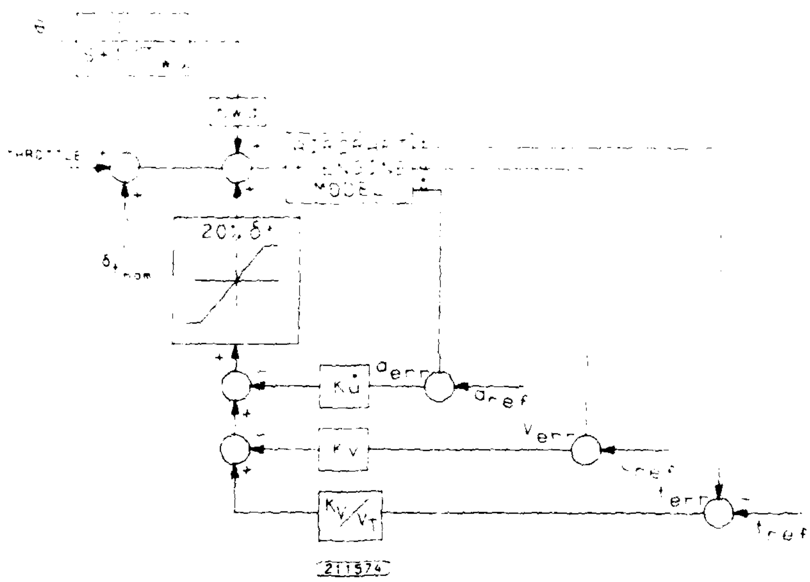
$$\phi_{CMD} = K_y \cdot y_{err} + K_{\dot{y}} \dot{y}_{err} + K_\phi \phi_{err}$$

Vertical path steering was achieved by computing a pitch attitude command and applying it to the vertical SAS yielding a stabilator deflection. This command is given by

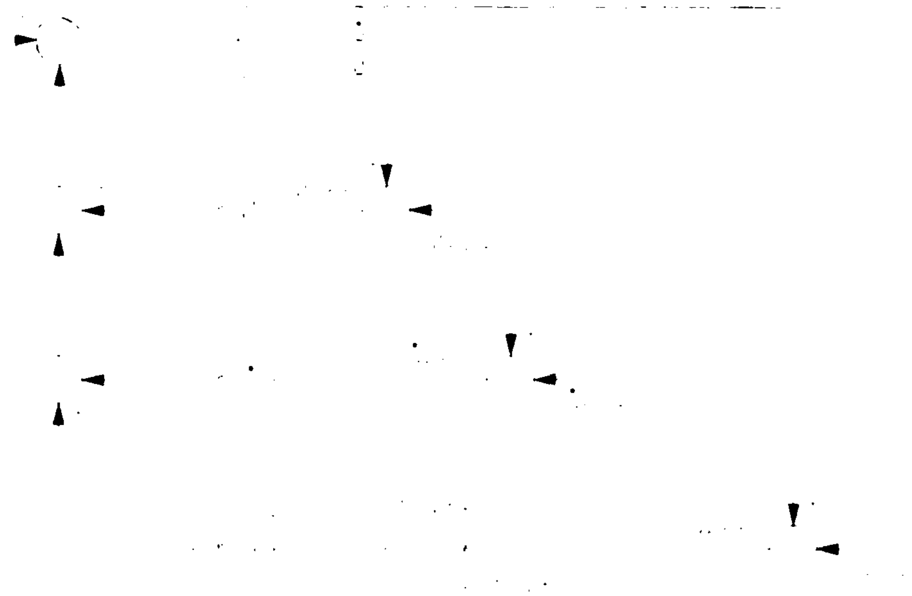
$$\theta_{CMD} = \left(\frac{K_h}{V_T}\right) z_{err} + K_\gamma \gamma_{err} + K_{\dot{\gamma}} \dot{\gamma}_{lag} + \theta_{LIFT}$$

The term $K_{\dot{\gamma}} \dot{\gamma}_{lag}$ was added in to θ_{CMD} for stability purposes. $\dot{\gamma}$ was filtered to attenuate the noise on this signal. The altitude error was gain scheduled as a function of true airspeed V_T because of varying system performance as a function of flight condition.

VERTICAL GUIDANCE CONTROL LAW BLOCK DIAGRAM
FIGURE 6-7



LONGITUDINAL GUIDANCE CONTROL LAW BLOCK DIAGRAM
FIGURE 6-8



LATERAL GUIDANCE CONTROL LAW BLOCK DIAGRAM
FIGURE 6-9

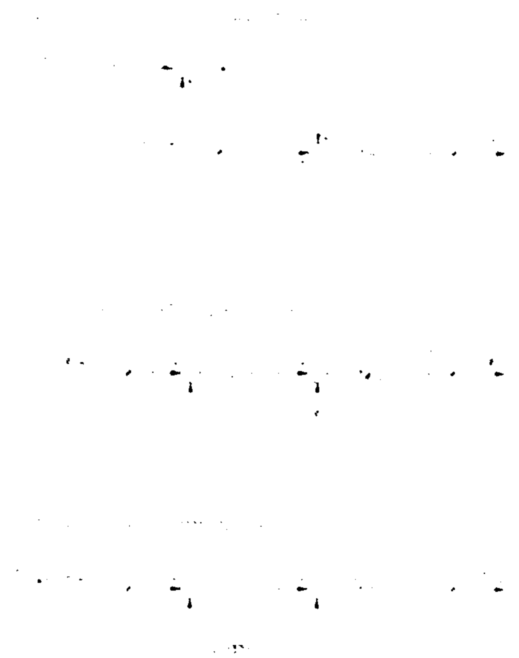
Longitudinal path steering was accomplished by computing an acceleration command and applying it to the autothrottle system yielding a throttle deflection. This command is given by

$$a_{CMD} = (K_T V_T) t_{err} + K_V V_{err} + K_{\dot{u}} a_{err} + K_\theta \left(\frac{s}{s + \frac{1}{\tau_{WO}}} \right) \theta$$

The time error was gain scheduled as a function of velocity as a result of varying system performance as a function of flight condition.

6.2.6 Flight Director

Pitch, roll, and throttle position commands were formed as shown in Figure 6-10 for display on the EADI. The aircraft pitch attitude -- which is subtracted from the synchronizer value of attitude obtained at mode engage -- is washed out in order to allow for trim changes resulting from changes in the aircraft flight condition. The resulting input is then scaled so that the upper limit of the flight director command gives maximum bar deflection on the EADI.



FLIGHT DIRECTOR COMMANDS BLOCK DIAGRAM
FIGURE 6-10

The roll flight director command was generated by limiting the roll command to + or -45 degrees and passing it through a lag filter in order to reduce the roll flight director bar activity resulting from navigation noise. The limited roll command is differenced with the aircraft roll attitude and scaled so that the maximum roll bar deflection corresponds to a + or -45 degrees difference between the commanded and actual bank angles.

The structure of the throttle position flight director is identical to the roll flight director.

6.2.7 Trajectory Redraw

If the pilot decides to override the autopilot by deflecting the side stick or throttle, the guidance errors have the potential of growing quite large. When the pilot has made a significant deviation from the 4D trajectory, the trajectory generator is requested to compute a new trajectory and consequently the guidance errors are nulled. The criteria for issuing a recomputation of the 4-D profile is

$$|y_{err}| > 3000.\ \text{ft}$$

$$|\dot{y}_{err}| > .866 \cdot V_T$$

$$|z_{err}| > 1000.\ \text{ft}$$

The criteria for issuing a recomputation of the speed-time profile is

$$|t_{err}| > 30\ \text{sec}$$

6.3 GUIDANCE NOMENCLATURE

Trajectory generator inputs:

Symbol(s)	Definition(s)
a_{21}	Acceleration on subsegment 3 prior to flight path angle change (ft/sec^2)
a_{22}	Acceleration on subsegment 3 after flight path angle change (ft/sec^2)
a_{41}	Acceleration on subsegment 5 prior to flight path angle change (ft/sec^2)
a_{42}	Acceleration on subsegment 5 after flight path angle change (ft/sec^2)
R_{IT}	Radius of initial turn (ft)
R_{FT}	Radius of final turn (ft)
s_{ST}	Length of straight line portion of waypoint pair trajectory (ft)
s_{TOTAL}	Length between waypoint pair (ft)
$s_{\Delta\gamma}$	Distance from "from" waypoint to change in flight path angle (ft)

Symbol(s)	Definition(s)
s_1	Length of initial turn arc (ft)
T_{IT}	Type of initial turn. $T_{IT} < 0$ indicates a right hand turn and $T_{IT} \geq 0$ indicates a left hand turn
T_{FT}	Type of final turn. $T_{FT} < 0$ indicates a right hand turn and $T_{FT} \geq 0$ indicates a left hand turn
V_{FS}	Airspeed specified at "from" way-point (ft/sec)
V_{IS}	Intermediate airspeed (ft/sec)
V_{TS}	Airspeed specified at "to" way-point (ft/sec)
V_{WIND}	Nominal wind magnitude (ft/sec)
x_{EPIT}, y_{EPIT}	Coordinates of end point of initial turn (ft)
x_{ITCTR}, y_{ITCTR}	Coordinates of center of initial turn (ft)
x_{FTCTR}, y_{FTCTR}	Coordinates of center of final turn (ft)
x_{SPIT}, y_{SPIT}, z_{SPIT}	Coordinates of starting point of initial turn (ft)
x_{SPFT}, y_{SPFT}	Coordinates of starting point of final turn (ft)
z_{EPFT}	Altitude of trajectory at end point of final turn (ft)
ψ_C	Heading of straight line segment (rad)
ψ_{WIND}	Wind direction (rad)
γ_{IB}	Inbound flight path angle (rad)
γ_{OB}	Outbound flight path angle (rad)

Reference trajectory variables:

Symbol(s)	Definition(s)
a_{ref}	Reference acceleration (ft/sec^2)
R	Radius of circular path being traversed (ft)
s	Distance traveled on from-to waypoint pair (ft)
ss	Distance traveled on the present subsegment (ft)
T	Turn type
t_{ref}	Reference time (sec)
V_g	Ground speed reference (ft/sec)
V_{ref}	Reference airspeed (ft/sec)
x, y, z	Aircraft position (ft)
(x_{CTR}, y_{CTR})	Coordinates of center of circle being traversed (ft)
$(x_{ref}, y_{ref}, z_{ref})$	Coordinates of reference position on trajectory (ft)
Δss	Incremental along-track distance (ft)
Δt	Time to fly incremental along-track distance Δss (sec)
$\Delta\psi$	Angle the aircraft has traversed during one real-time computation (rad)
γ_{ref}	Reference flight path angle (rad)
θ	Angle between wind vector and ground speed vector

Guidance Control law variables:

Symbol(s)	Definition(s)
a_{err}	Acceleration error (ft/sec^2)
C_D	Coefficient of Drag
C_{X_S}	Coefficient of drag along x stability axis
D	Aircraft drag (lbs)
g	Gravity constant (32.2 ft/sec^2)
MACH	Mach number
N_z	Normal acceleration (ft/sec^2)
Q	Dynamic pressure (lb/ft^2)
S	Wing reference area (530 ft^2)
s_{SWITCH}	Distance from discontinuity in vertical trajectory where flight path angle switching occurs (ft)
T	Thrust (lbs)
t_{err}	Time error (sec)
V_E	East component of airspeed (ft/sec)
V_{err}	Velocity error (ft/sec)
V_N	North component of airspeed (ft/sec)
V_T	True airspeed (ft/sec)
V_g	Ground speed (ft/sec)
W	Aircraft weight (lbs)
Y_{err}	Cross-track error (ft)
$\dot{Y}_{err}$	Cross-track rate error (ft/sec)
z_{err}	Altitude error (ft)
γ	Aircraft flight path angle (rad)

Symbol(s)	Definition(s)
$\Delta\gamma$	Flight path angle change (rad)
δt_{nom}	Nominal throttle position (%)
ρ	Air density (slugs/ft^3)
ϕ	Aircraft bank angle (rad)
ϕ_{err}	Roll attitude error (rad)
ϕ_{CMD}	Roll attitude command (rad)
ϕ_{ref}	Reference bank angle (rad)

7 CONTROL AND DISPLAY

7.1 CONTROL AND DISPLAY INTEGRATION

Providing the tactical fighter pilot with the capability of managing an on-board, real-time, four-dimensional trajectory generator imposes new requirements on the display system. Pilots now spend approximately 2-3 hours during the mission briefing and planning exercises for each hour of actual mission flight time. During this process they examine the weapon delivery area for easily identifiable features, type of target, best delivery heading and altitude, type of bombs and spacing, and defenses that are likely to be encountered. The total mission is analyzed to determine the best penetration and egress routes, suitable navigation points, fuel usage estimates, flight times, and alternate refuel and landing locations.

The pilot makes use of navigation planning maps and other printed material plus whatever information is available through intelligence sources. As a result of his mission preplanning, the pilot acquires a thorough understanding of the mission profile and tactical environment likely to be encountered.

The IFTC trajectory generator computes four-dimensional trajectories as a result of the original mission points and constraints plus performs modifications to the original profile as a result of mission changes. These may be as simple as a small capture profile resulting from a temporary mission deviation or as complex as an entirely new trajectory resulting from a command and control mission redirect.

As a result, the analysis of the control and display requirements identified two areas of display capability not found in current systems:

a. The displays must provide sufficient information to allow the pilot to view and assess the effects of any newly computed trajectory prior to making the acceptance or non-acceptance decision.

b. The displays must provide other confidence building and decision aiding information with respect to the command situation.

Research programs such as STOLAND [2] and Terminal Configured Vehicle (TCV) have demonstrated the usefulness of electronic map displays for conveying horizontal flight plan information to the pilot. Also identified was the need for an electronic alphanumeric display and keyboard for data entry and deletion.

The initial study of the IFTC application in a transport aircraft [1] utilized a display system consisting of an electronic attitude director indicator, EADI, an electronic map display, and an electronic status display for alphanumeric information. Also implemented was an electronically generated cross-hair symbol placed on the map and controlled by the pilot for rapidly creating or changing waypoint and trajectory information. The transport program also demonstrated the usefulness of having a fairly high level of computer-pilot interaction.

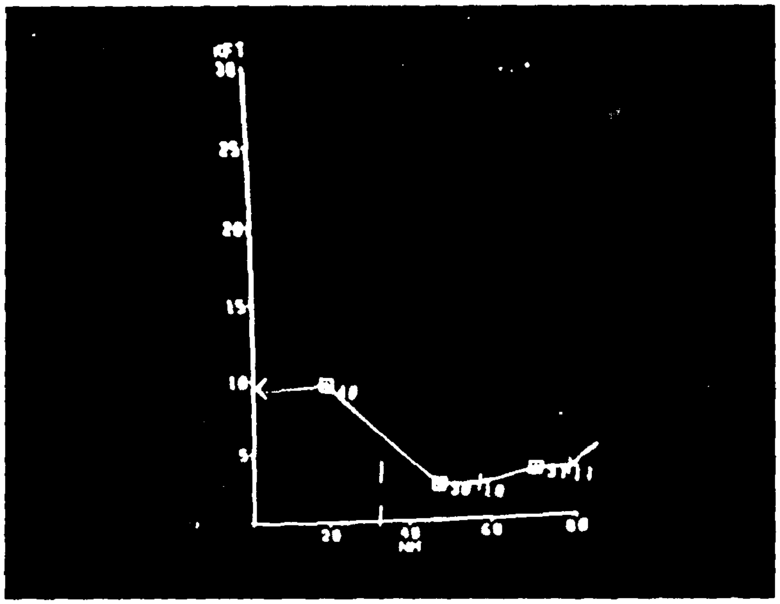
The control/display implementation for the fighter demonstration program was built on the knowledge gleaned from the transport program. Electronic displays provide attitude information with pitch, roll, and throttle commands; tactical situation information, with flight profiles, friendly and unfriendly aircraft positions, and SAM and AAA threat envelopes; and alphanumeric information with system and flight plan data.

The computer and pilot interaction design was developed to a higher level for the fighter program by providing mission oriented mode controls and increased man/machine interaction. The computer has been given more authority to make decisions with respect to the choice of display pages and map processing which in most situations reduces the pilot's button pushing activity.

The transport simulation also revealed the need for displaying vertical flight path information especially for flight management and crew awareness of computer generated spiral descent profiles, required by large vertically separated, but small laterally separated waypoints. A vertical flight path display mode (Figure 7-1) was implemented for the tactical program. In this mode the vertical flight plan is displayed as a function of along-track distance. The aircraft altitude is indicated by the "chevron" symbol fixed along the vertical altitude axis.

The display moves from right to left during flight. Map size and scaling choices allow about 80 nm of along-track distance to be displayed.

Use of the TSD mode selector buttons gives the pilot full access to both horizontal and vertical trajectory information.



TSD WITH VERTICAL FLIGHT PATH MODE SELECTED
FIGURE 7-1

The requirement for providing additional aircraft control system command information has been met in two ways. The first involves displaying the pitch, roll, and throttle commands on the EADI in a somewhat conventional fashion. (The EADI has since been removed from the cockpit to save space and replaced by an electro-mechanical three-axis ADI; pitch, roll, and throttle commands were preserved, however).

In addition to the EADI commands the vertical tape instruments were modified to allow the computer to drive the command altitude, airspeed, and Mach functions. Both the digital displays and the tape associated command pippers are driven. The command pippers provide the pilot with an immediate indication of the difference or error between his actual altitude (airspeed or mach) and the computer-generated desired altitude (airspeed or mach). The errors are viewed as the displacement between the pippers and the true indicators on the vertical tape instruments. The value of this capability is especially evident during periods of ascent or descent, and periods of changing airspeed. In current operations the pilot must manually set the command values corresponding to the next destination values. The error is meaningful only at the instant of destination flyover, when it's too late for corrections. By providing continually updated commands to the instrument, any error buildup with respect to the nominal 4-D profile is easily detected.

7.2 CONTROL/DISPLAY DESCRIPTION

The fighter cockpit and the controls and displays are shown in Figures 7-2, 7-3, and 7-4.

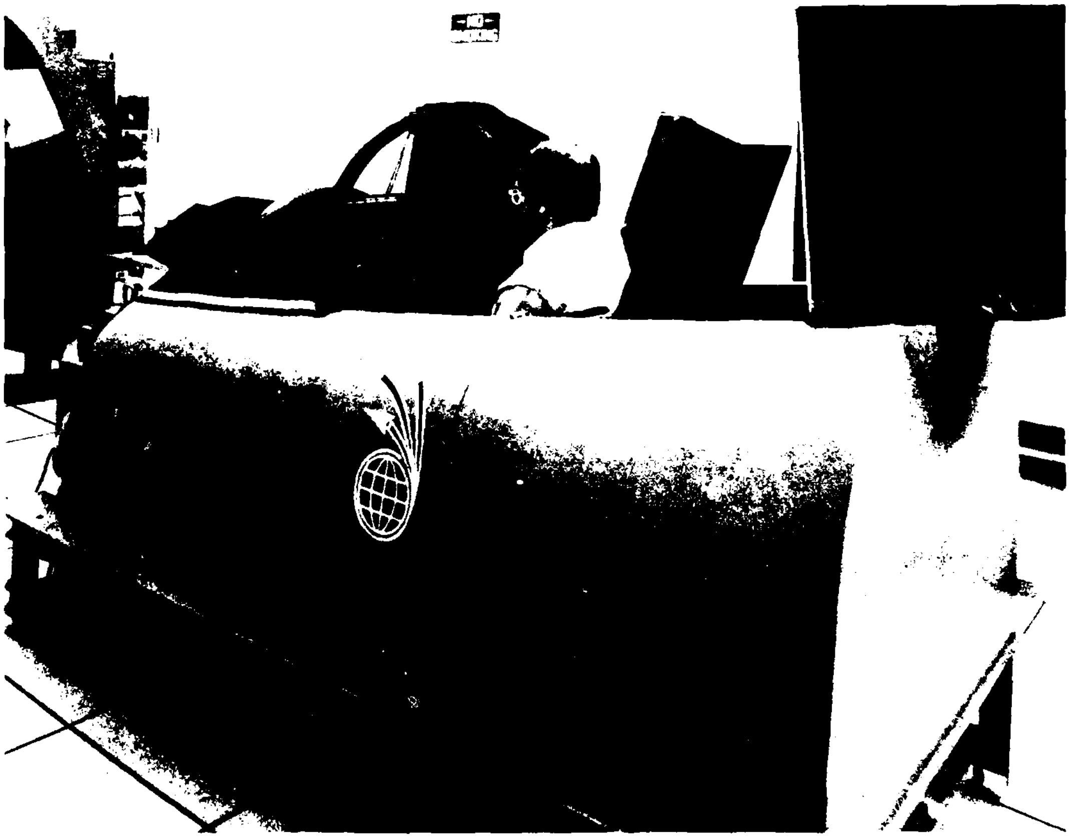
The following goals were established for the control/display design:

- Must be suitable for one-man operation
- Must consider the information requirements of the IFTC system and advanced command and control (C^2) operation
- Must provide mission-oriented mode selection
- Must extend the use of interactive control/display software to minimize the pilot's information management tasks
- Fully exploit the use of the trajectory generator as a means of providing the pilot with a higher level of decision-making information than would otherwise be possible
- Ultimate decision-maker must remain the pilot

The ar-angement of the controls and displays in the simulator is shown in Figure 7-3.

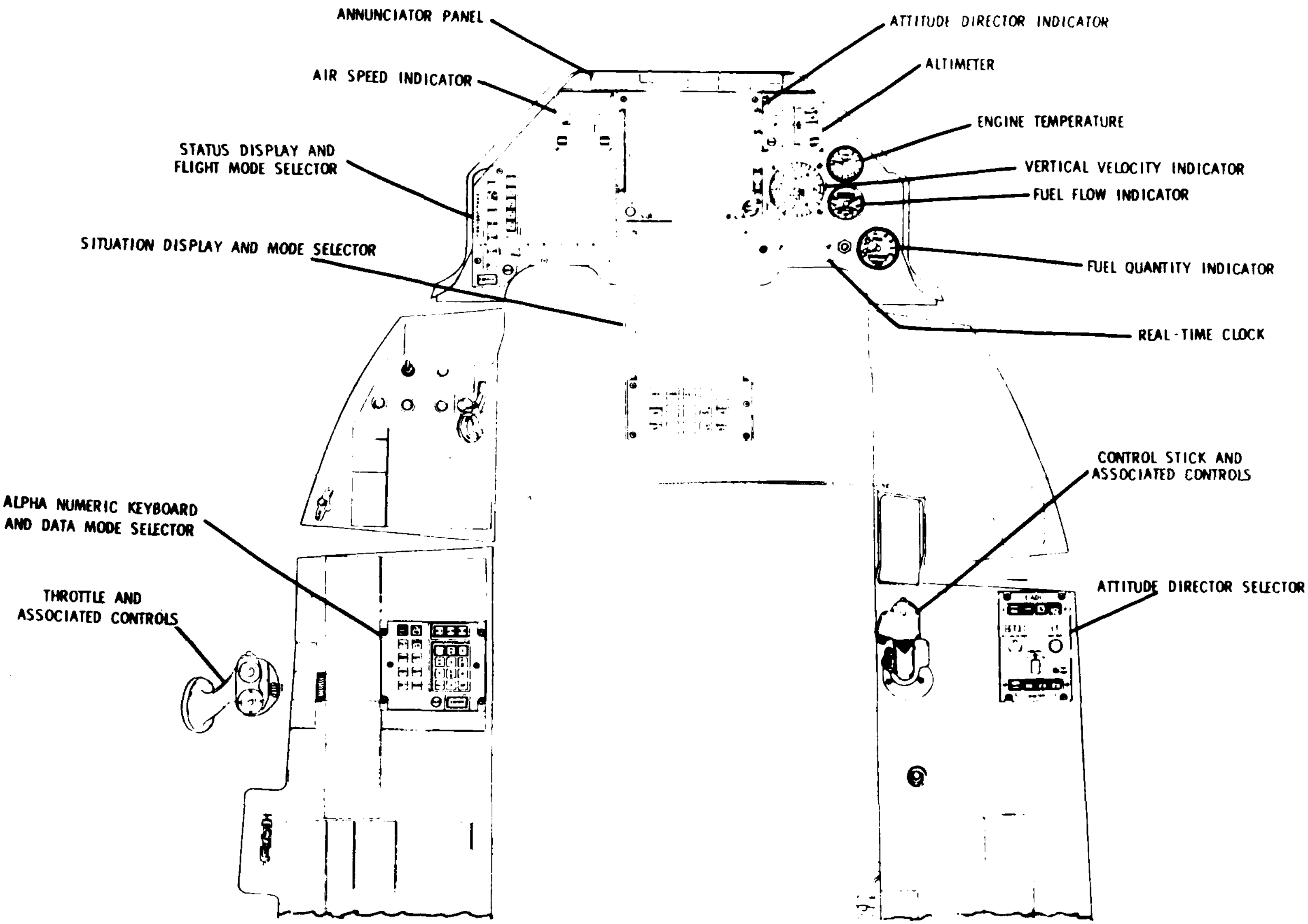
The following controls and displays are active:

- Annunciator lamps (on annunciator panel)
- Airspeed/Mach indicator
- Altimeter
- Electronic Attitude Director Indicator
- Electronic Status Display and Flight Mode Selector
- Tactical Situation Display and Mode Selector

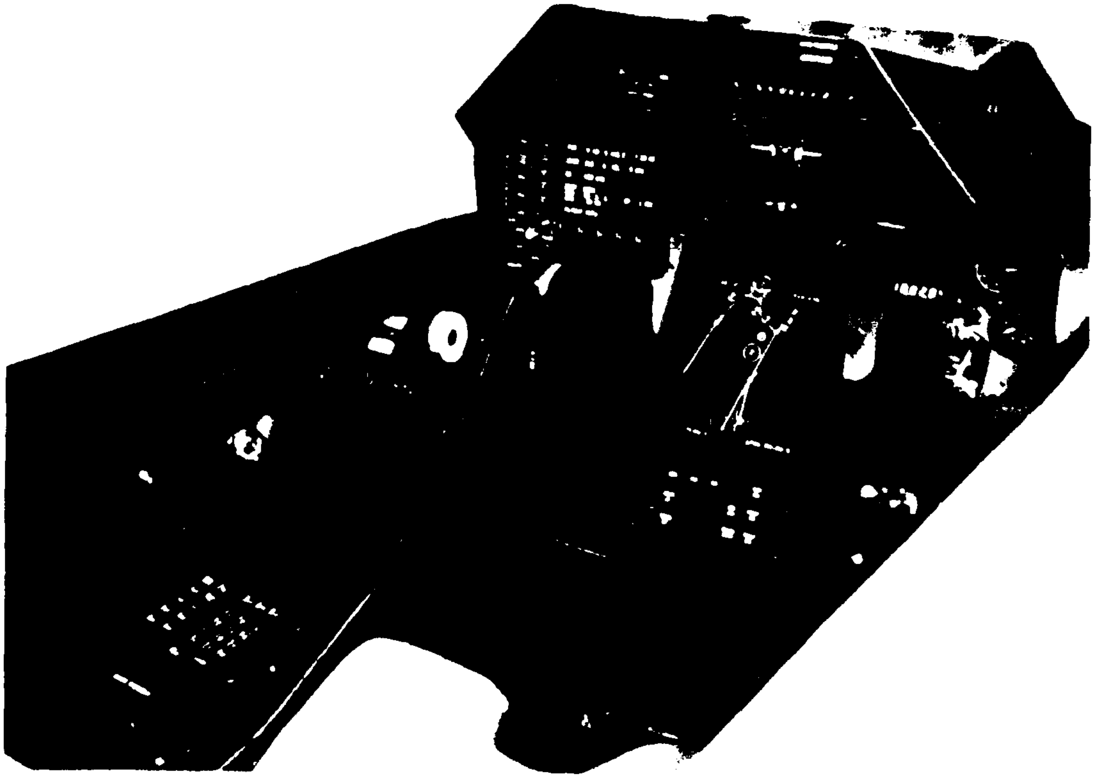


IFTC FIGHTER COCKPIT
FIGURE 7-2

- Alphanumeric Keyboard and Data Management Keys
- Throttle and associated autothrottle on-off switch
- Crosshair controller and associated Insert switch (both located on top of throttle)
- Control Stick with associated auto-flight on-off switch, weapon delivery enable switch, and pitch-roll trim switch
- Real-time clock
- Fuel remaining indicator



SIMULATOR CONTROLS AND DISPLAYS LAYOUT
FIGURE 7-3



IFTC COCKPIT DISPLAYS
FIGURE 7-4

- Vertical velocity indicator
- Gear up-down switch

The basic flight displays of aircraft attitude, altitude, mach and indicated airspeed are arranged in the normal "T-scan" pattern. Included at the bottom of the scan is the TSD and its associated mode keys. The status display and its associated flight mode keys is located on the left side of the front panel, just below the airspeed indicator. The alphanumeric keyboard and data management keys are located on the left console, below the throttle.

The side-stick controller is mounted on the right console, as is the EADI controller. The EADI controller is not required if the electro-mechanical ADI is used in place of the EADI.

The real-time clock, fuel gauges, and vertical speed indicator are located on the right side of the front console.

7.2.1 Tactical Situation Display

The Tactical Situation Display (TSD) has three fundamental display modes:

a. North-Up Oriented Horizontal Situation
b. Track-Up Oriented Horizontal Situation
c. Vertical Situation

In North-Up oriented mode, the map is stabilized with the north direction placed at the top of the display. The aircraft symbol moves and automatic recentering of the map about the aircraft position is initiated by the display processor as the aircraft nears the edge of the display. Manual recentering may be initiated by the pilot at any time by use of the CTR-ON-A/C key on the TSD mode panel.

North-Up mode is useful for in-flight mission planning and also allows the pilot a means of quick reorientation with respect to direction, following maneuvers which may result in disorientation.

Track-Up mode is used most often for the obvious reason that it relates directionally with the pilot's view through the canopy. In Track-Up mode the aircraft remains fixed relative to the display, as the map moves from top-to-bottom. In this mode no recentering of the aircraft is necessary, although the aircraft may be placed either near the bottom of the display or at the center. Depressing the CENTER-ON-A/C key places the aircraft at the center of the map, and allows a "behind-the-tail" view of the tactical situation. In a turn situation, resulting in changes of heading, the map rotates as well as translates, preserving the track-up orientation.

The Vertical Situation mode, previously described, is selected by depressing the VSD key. In all TSD modes the aircraft true position is displayed relative to the computed (desired) horizontal and vertical flight path.

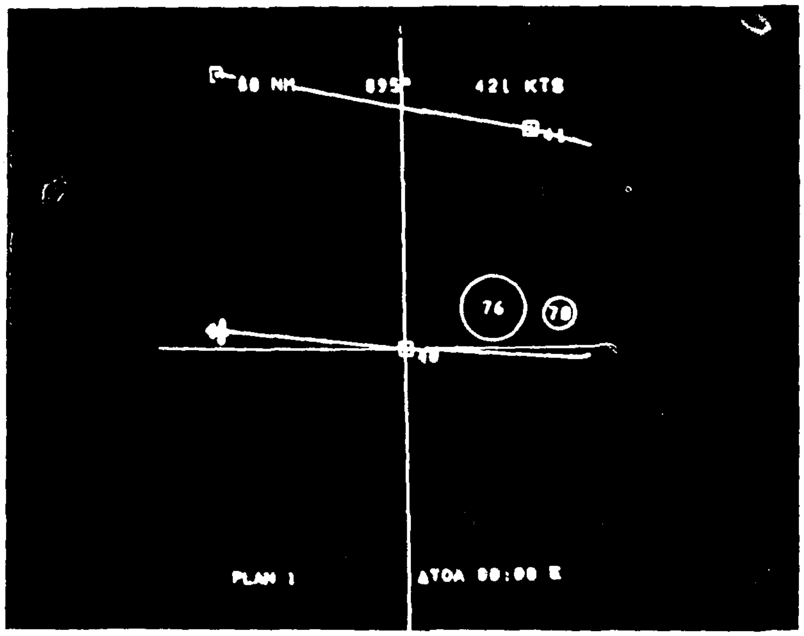
The following is a list and brief description of the classes of information presented on the TSD.

●	Aircraft Symbol	Fixed at display center while in the Track-Up mode; moving while in the North-Up mode
●	Alphanumerics	Explanatory and scaling information associated with scales and parameters (plan, heading, time of arrival, speed, time-of-arrival error)
●	Waypoint	Square, with numeric identifiers
●	Map Scale	Scale factor in nautical miles per frame (top to bottom)
●	Threat Information	Geographic location of threats such as SAM, AAA sites, and hostile aircraft
●	Target	Cross with numeric identifiers
●	Flight Path	Linking of waypoints by solid line indicates engaged profile, dashed line indicates planned profile not engaged.
●	Cross-x-hair	Full-scale crosshair controllable by a joystick mounted on the throttle handle

The X-hair, shown in Figure 7-5, is manually controlled by the thumb-activated force stick mounted atop the throttle as shown in Figure 7-10. Not normally in view, the X-hair is displayed by depressing the X-hair force stick. This action activates a switch which is sensed by the computer to initiate the display of the X-hair.

Once slewed to the desired position, the CTR-ON-X-HAIR key may be depressed which results in recentering of the map about the X-hair position. The X-hair is extinguished following this action. This capability is extremely useful when used with the SCALE INCrease key to "blow-up" portions of the map not near the aircraft position.

The X-hair may also be used to move points for modification of an existing flight plan as described in section 3, designate a "fly-to" point, or create a series of new points to be linked together to form a new flight plan. The procedures for performing the last two operations are



TSD WITH X-HAIR ACTIVATED
FIGURE 7-5

described later in this section. The X-nair is used primarily as a means of providing rapid pilot inputs without requiring extensive keyboard actions.

The X-hair may be used only when in the North-Up presentation, since the map is stationary. Activating the X-hair, as described, will result in the automatic switching to the North-Up mode if in the Track-Up or VSD modes.

Implementation of the X-hair in the Track-Up, moving map mode would require computer stabilization of the X-hair with respect to the moving map to augment the pilot's ability to track a moving point. In a non-turning situation and without computer-aided stabilization of the X-hair the pilot's inputs to the X-hair force stick must be a combination of that required to slew to the desired position plus that required to cancel the map translation motion. Release of the X-hair would result in its immediate drift from the desired position. Position error is the product of the ground speed of the aircraft and the time between release of the force stick and activation of the X-hair insert switch. The manual tracking problem becomes more difficult in turning maneuvers and enlarged map scaling.

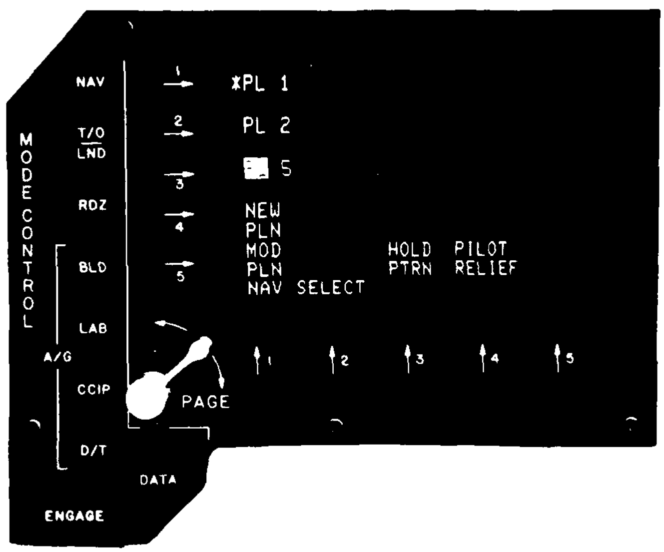
7.2.2 Status Display

The status display, shown in Figure 7-6, is a CRT used for displaying system mode, flight plan related data, and flight status information in alphanumeric format.

The status display is the pilot's primary interface to the IFTC system. It is an alphanumeric cathode ray tube display surrounded by 10 multifunction keys (five below the display and five to the left of it), a PAGE control, 7 mode selector keys, an ENGAGE key, and a DATA key.

The status display is capable of displaying 12 rows of 32 alphanumeric and special characters per row. The data field of the status display is divided as follows:

- Top row - Reserved for special annunciator messages
- 2nd, 4th, 6th, 8th, 10th rows - Aligned with the arrows on the five row selector keys to provide row selection multifunction key capability



STATUS DISPLAY AND MODE SELECTOR
FIGURE 7-6

- 12th row - Reserved for page identifiers

- Odd number rows - Data is limited to enhance readability of presented information

- Horizontally - Parameters titles are aligned vertically with column selector switches to provide the basis for a column selection capability

A cursor (dark characters on a light background) indicates the position designated by row and column selection. A single character length cursor indicates a data entry position. Selected modes are annunciated before engagement by a word length cursor.

The information is organized and displayed in "page" fashion with approximately 34 page formats currently implemented to handle the data requirements for the mission modes of navigation, blind weapon delivery, and rendezvous; waypoint, target, IP, and refuel point data; mission plan index data; data-link information; combination fly-to/X-hair data; and a map clutter/declutter select page.

Some page formats automatically place the cursor at certain data fields to cue the pilot to the importance of that information or to anticipate the pilot's selection of that field prior to depressing DATA or ENGAGE. This is an example of system anticipation of a probable pilot action, resulting in reduced button-pushing activity.

The cursor is also used to indicate data fields selected by the row-column keys bordering the display.

Mode related select pages are displayed as a result of depressing the MODE SELECT keys along the far left of the display. Examples of the mode select pages are shown later in Figure 7-12 for the Nav mode and in Figure 7-14 for the Blind mode.

Three simple actions are required for switching from one mode to another:

a. Select the proper mode from the seven mode switches.

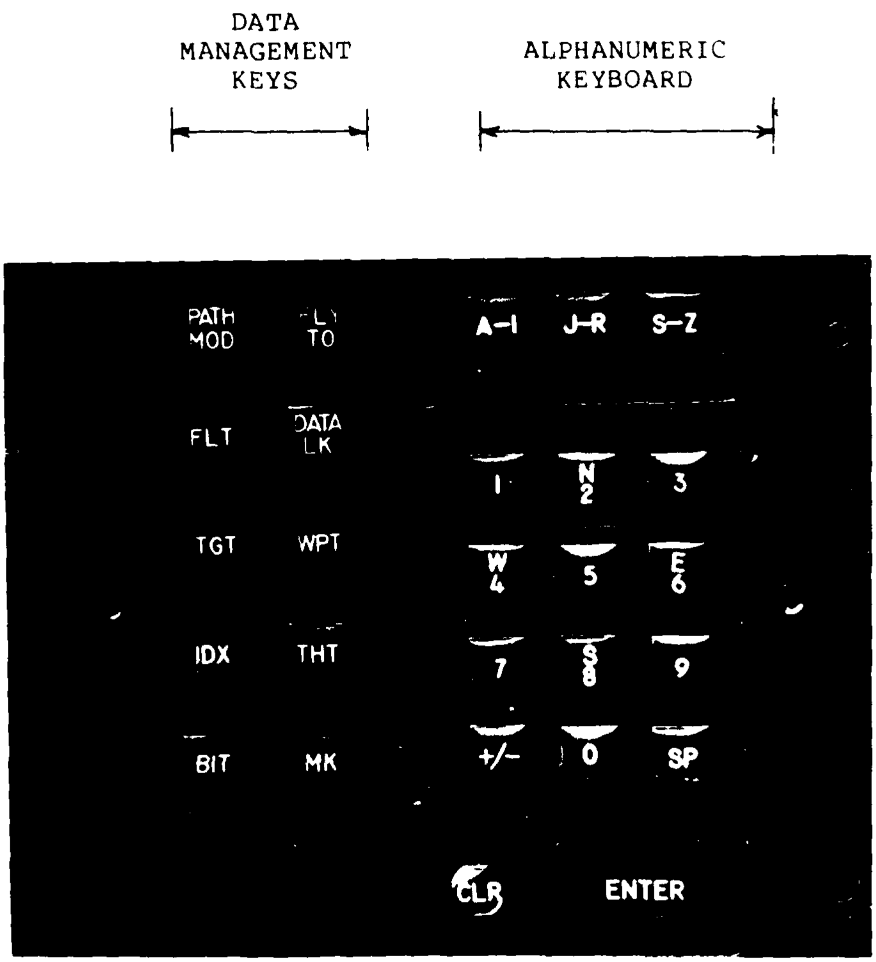
b. Review the mode-oriented select format displayed as a result of step a; edit as required.

c. Engage the mode by depressing the ENGAGE key.

The top line of the status display is never used by page-related information, but is always reserved for pilot advisory messages. Examples of advisory messages are: "LOW FUEL RESERVES @ WP__", "INSUFFICIENT DATA FOR TG__", & "C & C PLAN X REDIRECT".

7.2.3 Status Display Keyboard

This unit is mounted on the left console, as shown in Figure 7-7. It provides alphanumeric data entry capability to the system through the status display. The numeric keys are arranged in the 10-key matrix similar to the telephone "Touch-Tone"® system. Guards between the keys prevent inadvertent key actuations. The surface of the number "5" key is lower than that of the surrounding keys to provide a tactile feel for a "home" position. The 2, 4, 6, and 8 keys provide a dual function by providing for entry of the cardinal directions, N, E, S, and W.



STATUS DISPLAY KEYBOARD
FIGURE 7-7

Ten data modes are selectable for display on the status display by the data mode management keys on the left of the unit. FLY TO, FLT, TGT, WPT, and IDX were implemented for the simulation.

The functions of the additional data management keys, though not fully implemented, are intended to have the following use:

- PATH MOD — Allow pilot-initiated trajectory modifications such as path stretching, fuel economy select mode, maximum range, and lateral and/or vertical offset modes.
- DATA LK — Response select page for command/control data link messages (Figure 7-22).
- IDX — Index select page.
- BIT — Initiates the built-in-test functions of the airborne computer.
- MK — Used in-flight to freeze and record significant events and positions.

The alpha keys have been reduced from a full keyboard set to three multi-use keys. The alphabet has been divided in A-I, J-R, and S-Z as indicated on each key.

To initiate alpha entry into the selected data field, the pilot depresses the appropriate key which results in the display of successive characters in the data field. Two modes of operation are possible. The key may be held down and the alpha characters will cycle through the range for that key at a rate of approximately two characters per second (the rate is computer controlled and may be set to any reasonable value). The second mode of operation is to depress the key quickly and successively until the desired alpha character appears in the character slot. Release of the key, in either case, will cause the alpha character in view, to remain in view. After entry of an alpha character, the display is stepped forward to the next alphanumeric position by pressing the space key on the keyboard.

The keyboard and row-column keys are used until the pilot has edited an entire display page of information. This may be as simple as modifying one data field or as complex as filling the entire page with new data. The page data is buffered at the display (the computer is not aware of individual changes) and after inspection and acceptance by the pilot, the ENTER key is depressed. This action transfers the entire page of data to the computer for processing.

7.2.4 Time Display

The time display is located beneath the vertical speed indicator on the right side of the cockpit. This displays the time digitally in hours, minutes, and seconds, as shown in Figure 7-8.

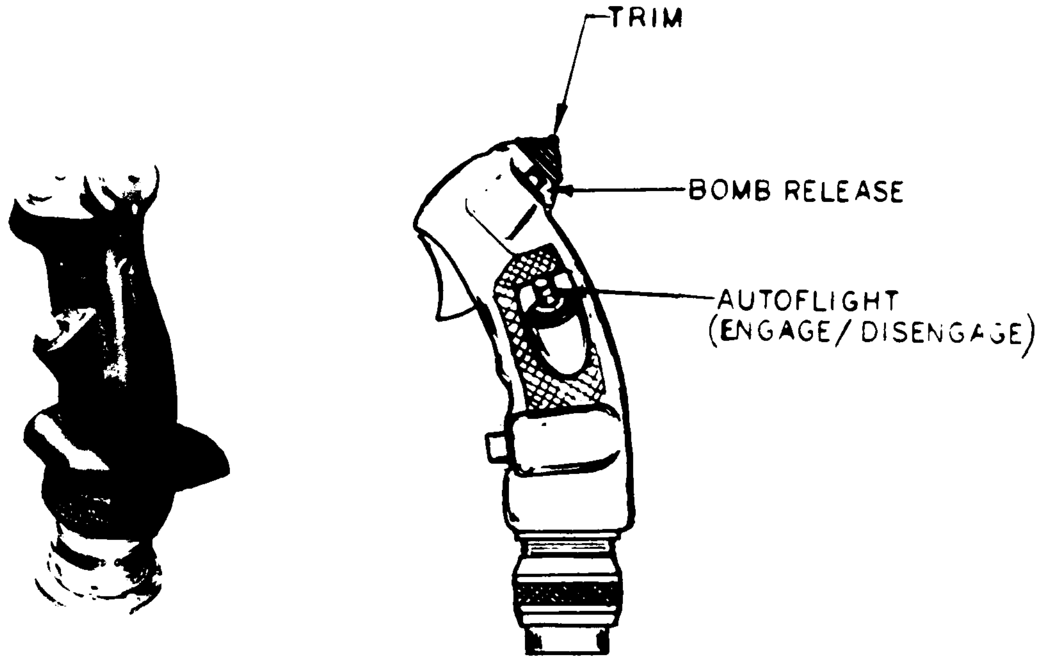
TIME DISPLAY
FIGURE 7-8

7.2.5 Aircraft Control Stick

The basic pitch and roll flight control capability is provided by a force-actuated control stick mounted on the right-hand console; it is shown in Figure 7-9. This capability is supplemented by a conventional "coolie hat" trim switch mounted atop the control stick.

Engaging or disengaging the 4D IFTC commands to the aircraft control surfaces is accomplished by pressing the thumb-activated autoflight switch. Autoflight operation is annunciated by illumination of the autoflight annunciator beneath the glare shield.

A thumb-activated "bomb release" switch is also mounted on the control stick as shown. Although other controls, such



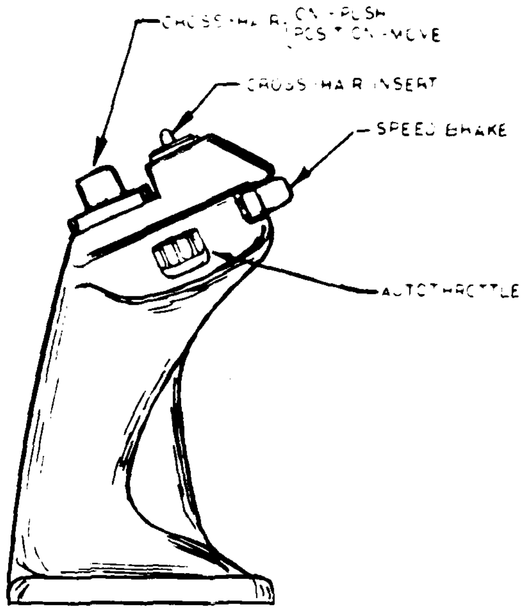
AIRCRAFT CONTROL STICK
FIGURE 7-9

as guns/rockets and intercom, are on the stick, only the pitch, roll, trim, autoflight, and bomb release functions are operational in the simulation.

7.2.6 <u>Throttle And Associated Controls</u>

Figure 7-10 shows the throttle as seen by the pilot. On it are identified the various switches. The throttle is cantilevered in-board above the left console. The throttle handle is hinged to fold upward to allow it to move into a forward detent position (afterburner).

Autothrottle operation is engaged or disengaged by successive depressions of the thumb-activated autothrottle switch. When autothrottle operation is engaged, the throttle is servoed to a computed thrust position by a closed-loop servo which is mounted beneath the left console and is driven by the computer. Autothrottle operation provides



THROTTLE AND ASSOCIATED CONTROLS
FIGURE 7-10

automatic speed control in response to flight control system outputs. An annunciator lamp indicates autothrottle engagement.

For speed brake actuation, the sliding switch positioned near the left forefinger is moved forward to extend the speed brake and aft to retract it.

Two controls on the throttle are associated with the operation of the crosshair (X-hair) symbol on the situation display. Depressing the rubber-covered, thumb-actuated, joystick causes the X-hair symbol to appear on the situation display. Applying lateral pressure to the joystick causes the X-hair symbol to move in a corresponding direction on the display. Depressing the thumb-actuated insert switch transmits a X-hair position on the situation display to the system computer for further processing.

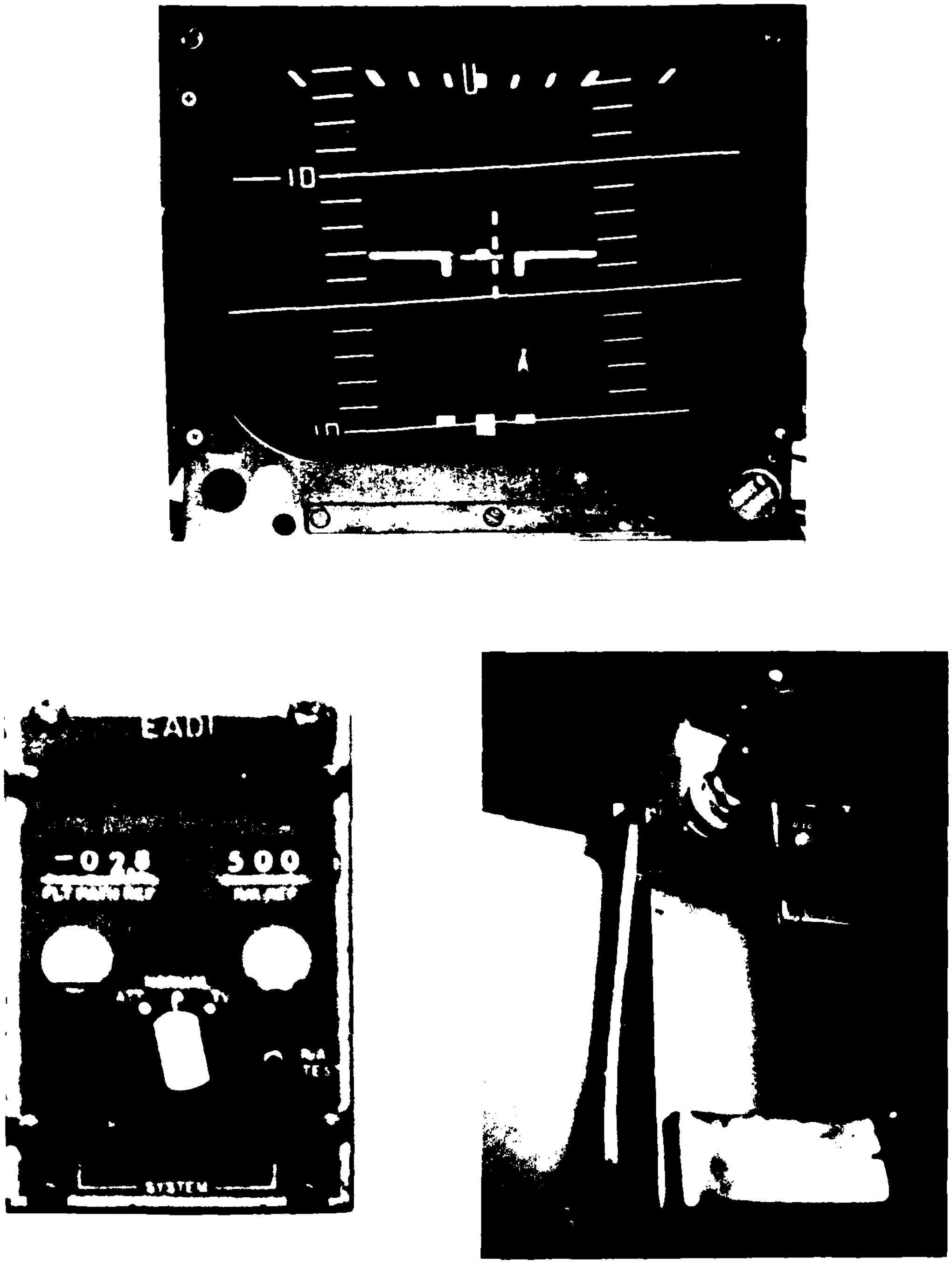
7.2.7 Electronic Attitude Director Indicator (EADI)

The EADI (Figure 7-11) is a cathode ray tube capable of displaying a wide variety of symbology pertinent to the mode selected.

a.	Aircraft Symbol	Fixed reference.
b.	Pitch Attitude	Sky-ground shaded division with 2° markings.
c.	Roll Attitude	10° markings at top of display.
d.	Flight Director Roll Command Pitch Command	Cross pointers. The pilot zeros the cross pointers to satisfy computed commands for the roll/pitch axis, e.g., capture and track of a desired waypoint (latitude, longitude, and altitude).
e.	Throttle Command	A vertical bar on the left wing of the aircraft. This bar moves up or down to command a speed increase or decrease. The pilot adjusts the throttles to zero the command to achieve "time" constraints (speed/arrival time).
f.	Radar Altitude	Numeric display - This is shown in the upper right portion of the screen. Radar altitude is active below 1200 ft.
g.	Rate of Turn	Self-explanatory.

7.2.8 EADI Controller

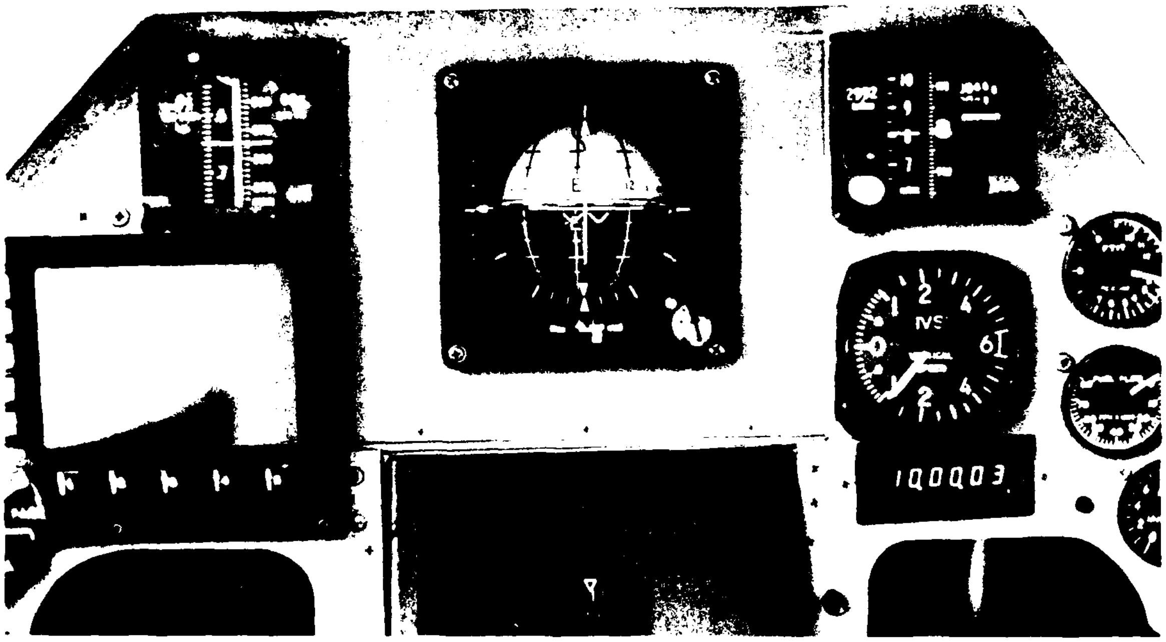
The EADI controller is mounted on the right console as shown in Figure 7-11. Its function is to enable the pilot to select information for display on the EADI. Since the IFTC program was not concerned with studying EADI symbology, the controller was used only to add or remove the flight director symbology for roll, pitch, and throttle commands.



ELECTRONIC ATTITUDE DIRECTOR INDICATOR AND CONTROLLER
FIGURE 7-11

7.2.9 Attitude Director Indicator (ADI)

The EADI is interchangeable with a three-axis electro-mechanical ADI as shown in Figure 7-12. The ADI provides pitch and roll attitude information as well as pitch, roll, and throttle command needles. Aircraft azimuth is also displayed.



THREE-AXIS ATTITUDE DIRECTOR INDICATOR
FIGURE 7-12

7.3 PILOT OPERATIONS

Pilot operations necessary to use the IFTC system are consistent with current cockpit procedures and greatly reduce the navigation workload for time-critical missions.

These operations include:

- Selection of operational modes such as navigation, rendezvous, and weapons delivery.

- Insertion of a flight plan and modification, as necessary, by changing the specific time-space coordinates while enroute.

- Monitoring or controlling the actual flight path to follow the flight plan.

Such operations are simplified by interactive computer aiding of the controls and displays that comprise the pilot/system interface and which utilize:

- Dedicated flight mode select switches.

- Joystick-controlled X-hair on the TSD for easy enroute flight plan modifications and an alphanumeric keyboard and status display for editing of both on-board generated and ground-commanded data.

- Automatic control of time-critical navigation. This allows pilot time for direct visual search for bogies, and command/control data management.

7.3.1 Mode Selection

Mode selection is made using the Mode Controller keys located to the left of the Status Display. Seven basic flight modes are selectable:

- Navigation (NAV) for point-to-point curved path navigation between waypoints,

- Takeoff and landing (T/O/LND) for terminal area control,

- Rendezvous (RDZ) for in-flight refueling and formation flights, and

- Four air-to-ground weapon delivery modes:

    - Blind (BLD)

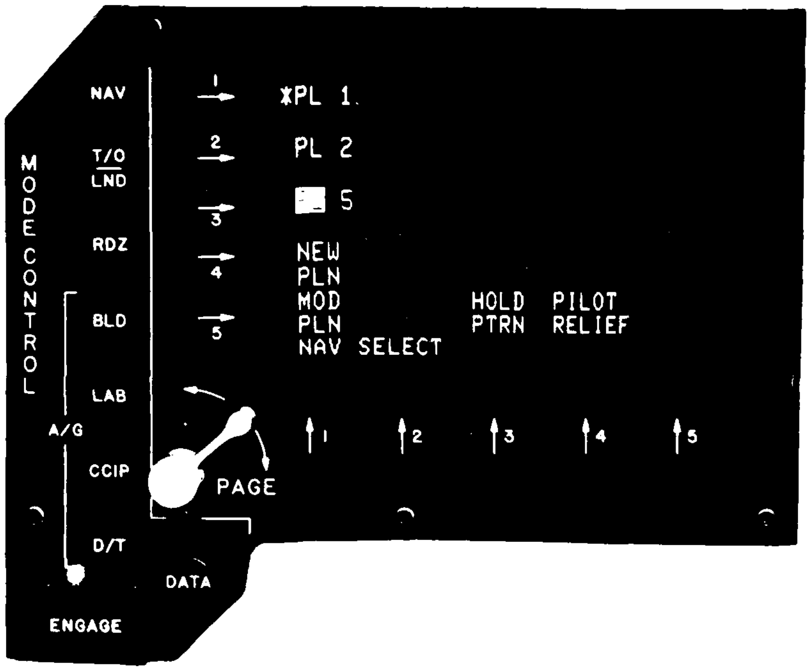
    - Low Altitude Bombing (LAB)

    - Continuously Computed Impact Point (CCIP)

    - Dive Toss (D/T)

Of the modes selectable on the mode controller, two were required for the current IFTC program, Navigation and Blind Weapon Delivery.

The Navigation Select page is shown in Figure 7-13.



STATUS DISPLAY AND MODE SELECT KEYS - NAV SELECT PAGE
FIGURE 7-13

Seven pushbutton switches arranged vertically along the left side of the unit enable the pilot to select the basic flight mode of the aircraft. Depressing a mode switch causes a page of mode-related information to be displayed on the status display. This is referred to as the (NAV, BLIND, etc.) MODE SELECT page.

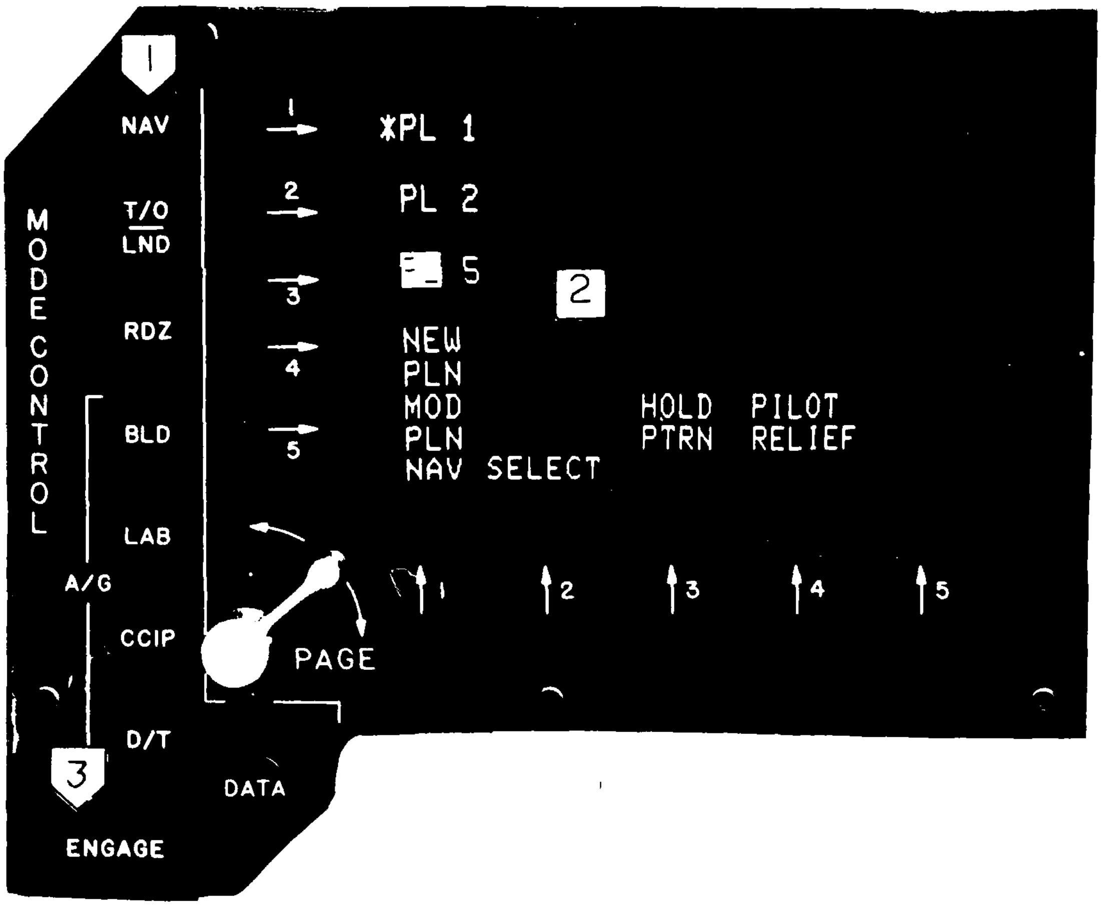
A complete mode selection sequence consists of:

1. Select and actuate the desired mode switch.

2. Select the desired action on the status display using the mode select page.

3. Press ENGAGE to engage the selected mode for IFTC trajectory computation and control.

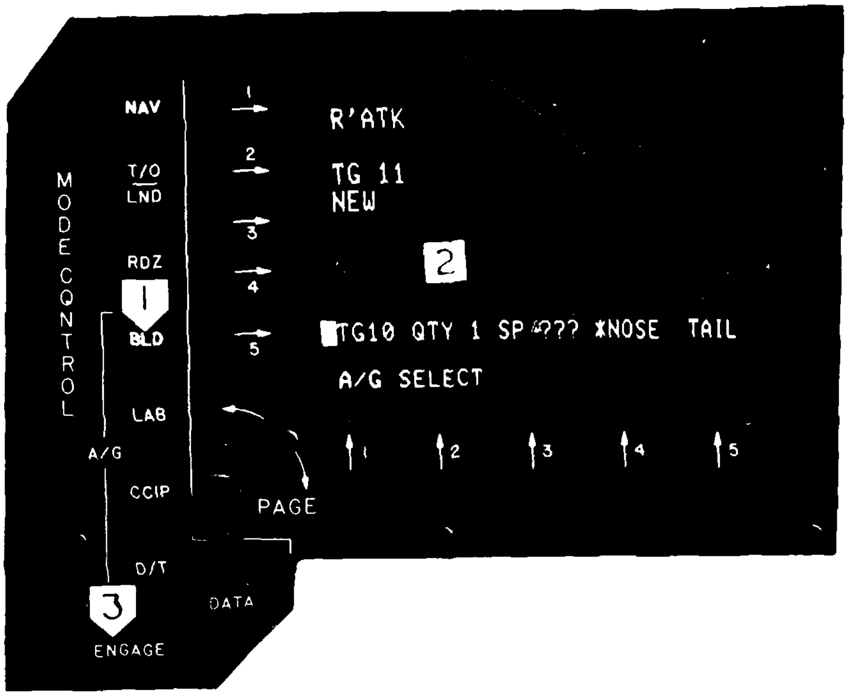
The first step requires selection of the appropriate mode such as pressing the NAV key. This places the NAV SELECT format on the status display. The NAV SELECT format offers a choice of the various plans that are stored in the system. Each plan consists of multiple waypoints defined by latitude, longitude, altitude, and, where necessary, time of arrival or other profile-related parameters. The highlighting cursor (reverse video) will be positioned at one of the plans. This cursor may be repositioned, if desired, by pressing the adjacent row select key. The position of the cursor will change, indicating the plan that will be engaged by pressing the ENGAGE button. This three-step sequence is illustrated in Figure 7-14.



THREE STEPS TO ENGAGE THE SELECTED MODE
FIGURE 7-14

A similar sequence engages the other modes. Pressing the RDZ key brings the rendezvous select format in view on the status display. The highlighting cursor will be positioned at the refuel tanker number indicated by the plan being flown. If it is desired to change the refuel number, it is done easily by moving the cursor using the row select multifunction buttons. After the information has been verified on the status display, the pilot needs only to push the ENGAGE button to initiate the refueling sequence at the refuel location shown on the status display. The Rendezvous mode was not demonstrated during the simulation testing.

Blind air-to-ground weapon delivery is selected by depressing the BLD key, verifying the target identification cued by the cursor on the status display, and determining that the quantity, spacing, and fusing of the weapon are correct for the particular air-to-ground mission. Depressing the ENGAGE key engages air-to-ground weapon delivery. Continuous depression of the "pickle" switch after an in-range indication is required to arm the system to enable weapon release. Figure 7-15 illustrates the steps required for engaging the Blind Weapon Delivery mode.



THREE STEPS TO ENGAGE THE BLIND WEAPON DELIVERY MODE
FROM THE BLIND SELECT PAGE
FIGURE 7-15

7.3.2 Waypoints

The basic position element in the IFTC system is the waypoint. A waypoint is any position definable in x, y, and z coordinates. Normally, these coordinates are given in latitude, longitude, and altitude, and, if required, time of arrival at that waypoint. For convenience in this system, these basic position elements are categorized as waypoints, targets, target initial (or identification) points, refuel initial points, and refuel couple points.

In the IFTC system, these points have been arranged into numerical groups as shown in Table 7-I. The use of these number groups reduces the system and operator alpha entry requirements and consequently reduces entry time for specifying a particular point.

The status display programming recognizes the categories listed in this table. Entering a number from one of these categories on the status display, where requested, will result in the addition of the proper two-character alpha identifier, preceding the number on the status display.

TABLE 7-I
POINT CLASSIFICATION CATEGORIES

Data/Point Classification	Number Assigned	System Abbreviation
Own Aircraft	00	AC
Plans	01 - 09	PL
Targets	10 - 19	TG
Refuel Initial Points	20 - 24	RF or RFIP
Refuel Couple Points	25 - 29	RFCP
Air-to-Ground Initial Point	30 - 39	IP
Waypoints	40 - 69	WP

7.3.3 Waypoint Entry Description

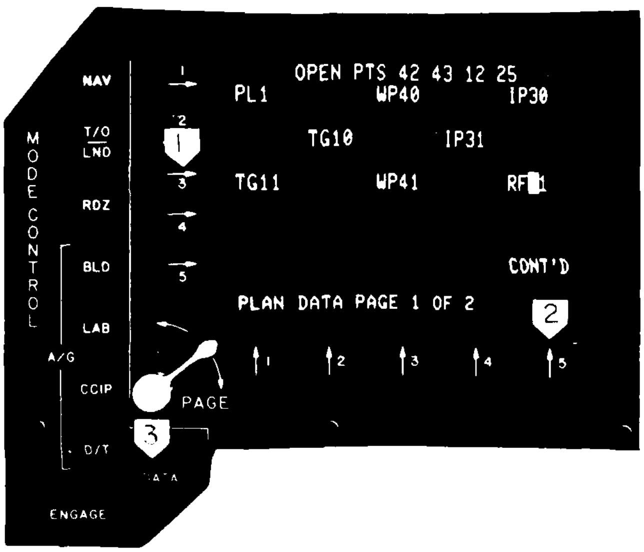
Waypoint types (Nav point, IPs, Targets, and Refuel points) are assigned a permissible range of numeric identifiers as described. When the WP or TGT special keys are used to place a blank waypoint or target page on the status display, only numbers in the proper range for the display page will be accepted as keyboard inputs. Attempt at entry of those outside the range will be ignored, i,e., if numbers outside the range of 40-69 are attempted to be entered on a waypoint page, the entry will not be accepted.

In those situations for which a blank, general waypoint page is placed on the status display, keyboard entry of a numerical identifier will result in the automatic designation on the display of the waypoint type according to Table 7-I. As an example, if "41" is entered, "WP41" will appear on the status display. If "10" is entered, "TG10" will apear. In general, the blank waypoint page is placed on the status display as a result of using the FLY-TO key or the X-hair controller.

In all cases, the status display will list several available point identifiers at the top of the display page. These are used by the pilot and make it unnecessary for him to maintain the bookkeeping for assigned and unassigned identifiers.

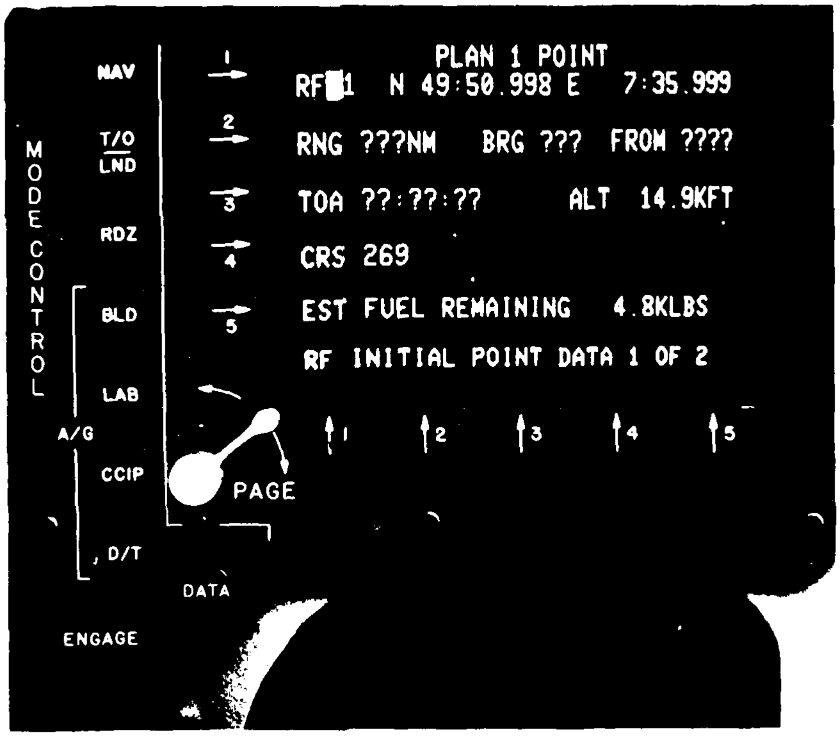
7.3.4 Flight Plan

A flight plan is input to the IFTC system by specifying a group of waypoints in an ordered sequence. This ordering may be done either prior to the flight and input to the system via memory transfer, or it may be done during the flight by the pilot or by data link inputs. A typical flight plan is shown on the status display in Figure 7-16.



RF21 IS SELECTED AND DATA IS DEPRESSED
FIGURE 7-16

All flight plans begin at the present position of the aircraft. The first point in this particular plan is Waypoint 40. This is followed by weapon delivery Initial Point 30 (IP30) and Target 10 (TG10). The flight sequence of the points on the plan page is read left to right and top to bottom. Specific information for any of the plan points is displayed by depressing the proper row column buttons corresponding to the desired point, followed by depressing the DATA key. The sequence for displaying information for RF21 is shown in the figure. Figure 7-17 is the page displayed following step 3.



DATA FOR RF21 IS DISPLAYED
FIGURE 7-17

7.3.5 Plan Generation With the Keyboard

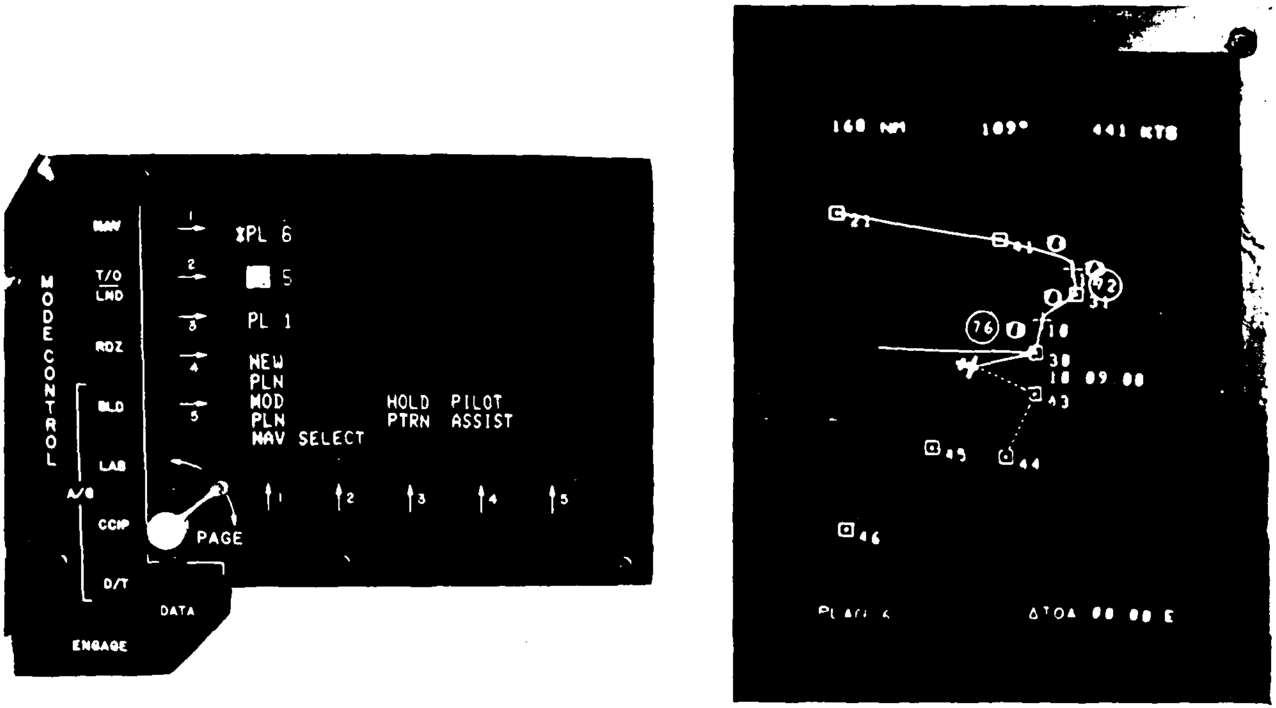
Any point on the plan may be changed by the row/column selector keys. This is accomplished by pressing a row and column key corresponding to the location of the point to be changed. The cursor will be positioned at the selected location and the existing point may be deleted and a new point entered via the keyboard. Data for an existing point may be modified using the previous procedure to display the specific data for the point in question. The keyboard is used for data modification.

In addition, open data fields are provided before and after each point on the plan page to enable the pilot to "add" points to a plan. Points are deleted from the plan by row/column selection and operation of the CLR (Clear) key.

After building a plan, the ENTER key is pressed to transmit the sequence of points to the IFTC computer for generation of a trajectory between the points. The resulting plan is shown as a dashed line on the TSD. The newly computed plan is assigned a name and the NAV SELECT page is automatically displayed with the cursor over the new plan name in anticipation of pilot engagement. The TSD and status display are shown in Figure 7-18.

The asterisk on Plan 6 indicates that steering commands are being generated to fly the aircraft to the solid line trajectory with that particular plan number as shown on the TSD. The dashed line trajectory has been assigned Plan 5. The highlighting cursor on the status display indicates that Plan 5 may be engaged by pressing the ENGAGE button. If the pilot wishes to review the point data of Plan 5, he may push the DATA key. This will return the status display to the Plan 5 data page from which points may be selected for review.

Engagement of the new Plan 5 results in an update of the TSD with the removal of the old trajectory, 6, and the redrawing of the new, 5, in solid format. If autoflight is engaged, the A/C control system will respond immediately. If critical data for a particular point in the plan has been omitted, the computer will return the appropriate data page to the status display with a message on the advisory line indicating the data requested.



TSD AND STATUS DISPLAY AFTER ENTERING A NEW PLAN
FIGURE 7-18

7.3.6 Plan Generation With the X-Hair

The previous example described the keyboard use for entering a flight plan, which was then engaged to the flight control system. The X-hair controller may also be used for creating a flight plan. This may be accomplished in three ways:

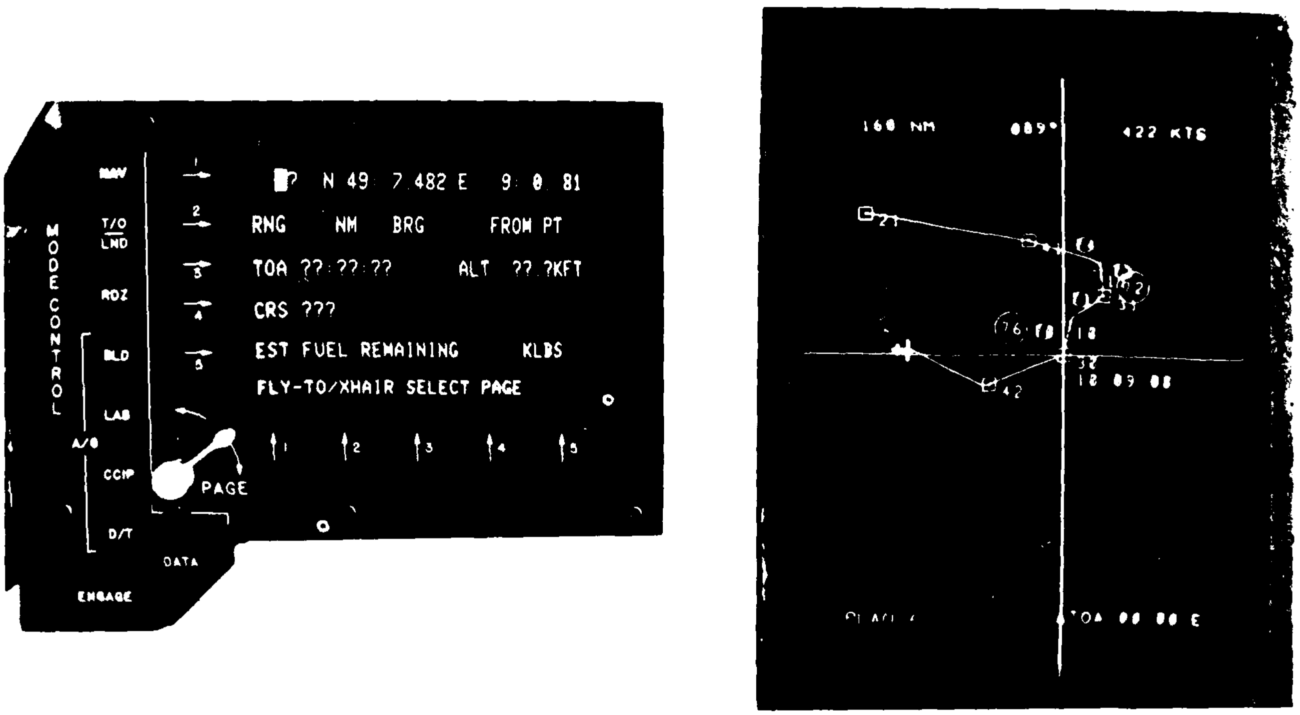
a. Modify a point or points in an existing plan. The modification may involve movement of the point or respecifying other point parameters such as time-of-arrival or fly-over heading. An example of this type is described in the demonstration profile.

b. Modification of an existing plan by adding one or more new waypoints.

c. Creation of a plan consisting of new waypoints.

As described, the X-hair is brought into view by depressing the X-hair controller located on the throttle handle. To "hook" an existing plan point it is necessary to slew the X-hair until it lies over the point. While slewing, the X-hair coordinates are continually updated and displayed on the FLY-TO/XHAIR SELECT PAGE on the status display (Figure 7-19). After proper positioning, the INSERT button is depressed. The system computer searches for an existing nav point (target, IP) that is positioned within 2 nmi of the X-hair position. If the search is successful, a message on the status display indicates which point was "hooked" and of which flight plan it is a part. The FLY-TO/XHAIR SELECT page is automatically replaced by the page of data for the successfully "hooked" point. If the "hook" was unsuccessful, that fact is indicated also.

The X-hair remains on and may now be slewed to the new, desired location. Following insertion at the new position, the trajectory generator computes a new profile which is drawn on the TSD in predictive format.



X-HAIR DISPLAYED ON THE TSD WITH THE FLY-TO/XHAIR SELECT PAGE ON THE STATUS DISPLAY
FIGURE 7-19

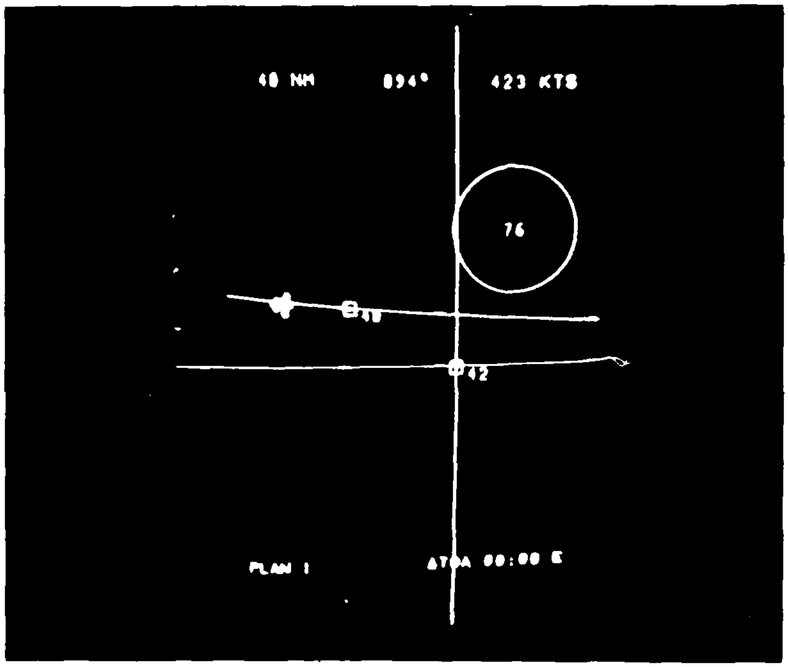
The new plan may be inspected and engaged by the pilot. The same procedure may be repeated to modify additional points in the existing plan.

New waypoints or targets may be created by first depressing the TGT or WPT button on the keyboard. This results in the display of a blank waypoint or target page and an advisory message at the top of the display indicating the identifiers of two available, unused points. At this point the pilot has the option of either using the keyboard or the X-hair for specifying the point. The keyboard may be used to manually enter an identifier, latitude, longitude, and any other allowable parameters. ENTER is depressed following the data entry.

To use the X-hair, it is turned on as described, and slewed to the desired position. This desired position for X-hair use should be a point relative to other map features. It is not intended to be used to match a set of given coordinates. Following insertion of the X-hair location, the computer will assign an available and appropriate identifier and create a point at the X-hair location. The X-hair is removed from the TSD and the new point appears at X-hair location, as shown in Figure 7-20. The procedure is repeated until the desired number of waypoints have been created and drawn on the map.

The group of waypoints and/or targets have been created but have not been connected in any particular sequence to form a plan. The map shows the location and identifiers of the points (when in HSD mode) but has no profile connecting them. The pilot defines a new plan using these points and any other defined points by the following sequence:

Action	Result
• Depress NAV mode key.	Nav select page on status display.
• Depress row and column for NEW PLN and depress DATA	Blank plan page on status display.
• Use keyboard to enter waypoint (target, refuel) identifiers in desired sequence to be flown	Point identifiers forming plan appear on status display.



NEW WAYPOINT CREATED WITH THE X-HAIR
FIGURE 7-20

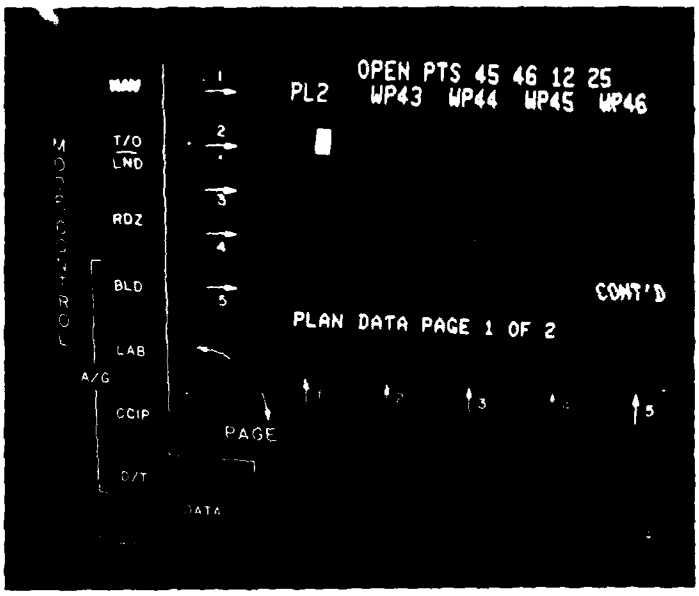
• Depress ENTER when list is complete	New plan is formed by computer, assigned a plan number, and the trajectory is drawn on the map, through the points and in predictive format. The Nav select page is automatically placed on the status display with the cursor placed over the new plan name.
• Inspect new plan on map and depress ENGAGE key, if desired	New plan is redrawn on map in solid line format. Autoflight system, if engaged, will begin to fly aircraft along the new plan. Any old plans are erased from the map.

Prior to performing the last step, the pilot may use the status display to examine specific data for any points included in the plan. This data is flight plan related and includes such parameters as estimated times-of-arrival, maximum and minimum times-of-arrival, and fuel remaining estimates.

It should be emphasized again that it is not intended for the pilot to use the X-hair controller and the latitude and longitude position of the X-hair as indicated on the status display to position the X-hair at some given latitude and longitude. To do so would require extreme hand and eye coordination among the X-hair controller, status display, and the map. While marginally possible in the simulator, this operation would be impossible in a real cockpit under flight conditions.

Points used in the creation of a new plan may be combinations of newly created points and previously existing points.

A capture segment is always drawn on the map which connects the current aircraft position with first point in a newly created plan. An example of a X-hair generated plan using the New Plan page on the status display is shown in Figure 7-21.

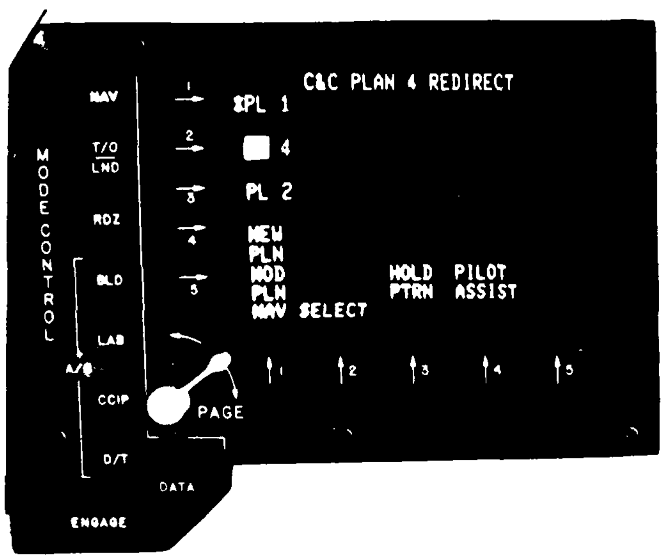


POINTS LINKED IN ORDER TO CREATE A NEW PLAN
FIGURE 7-21

7.3.7 Plan Generation With Digital Data Link Inputs

The IFTC system is designed to operate with advanced digital data link concepts, such as JTIDS. As an example of its compatibility with JTIDS, the IFTC system has the capability of receiving mission redirect information consisting of multiple waypoints and the latitude/longitude of those waypoints. Times-of-arrival may also be assigned to critical points in the redirect plan. In a transmission of this nature, the data link annunciator light on the glare shield illuminates, indicating that data link information has been received.

The incoming plan and waypoint position data are processed by the IFTC computer. The trajectory generator computes a profile based on the incoming plan information. The resulting trajectory or plan is displayed on the TSD as a dashed profile through the new waypoints. It is assigned a plan number, the NAV SELECT page is automatically displayed, with the highlighting cursor placed adjacent to the newly input data link plan, as shown in Figure 7-22. In addition, the message, "C&C PLAN 4 REDIRECT" appears at the top of the status display.



DATA-LINK MISSION REDIRECT
FIGURE 7-22

The pilot has the option of either engagement through the normal ENGAGE function or data search with the DATA key. The data link annunciator on the glare shield is extinguished when the pilot presses either ENGAGE or any other key in the system.

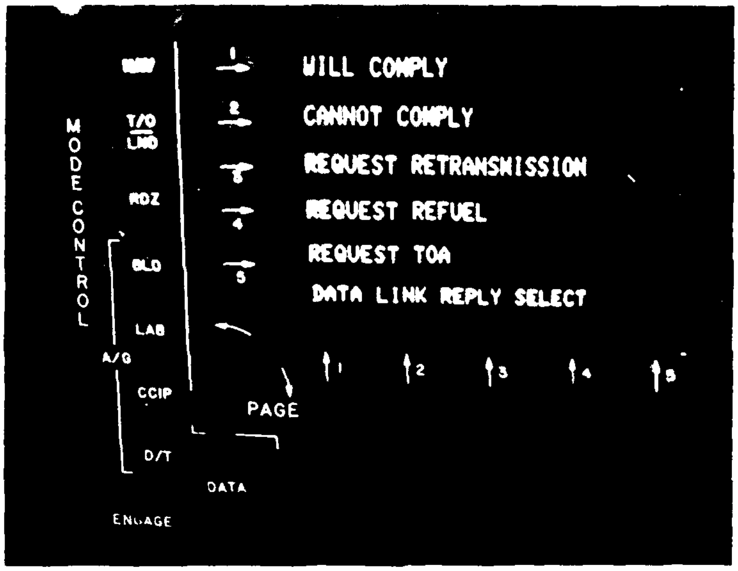
The IFTC system is capable of receiving individual waypoint updating information. As an example, the coordinates of a particular target in the system may be updated. The receiver transmits the incoming waypoint information as an update to the waypoint memory storage. The coordinates or other parameters are updated and a message annunciating that fact appears on the top line of the status display.

Other examples of the kind of information that may be received via the data link are hostile and friendly aircraft positions and surface-to-air missile sites. The type of threat and its location is received via the data link receiver. This information is processed by the IFTC system, and is translated into appropriate SAM, AAA, or hostile A/C symbology on the TSD. Any intersection of the profile and a ground-based threat envelope is determined. An alternate trajectory is generated and displayed on the TSD in predictive format. The nav select format is presented to the operator and the pilot is given an opportunity to inspect and engage the dashed line plan via the normal IFTC control and display functions. Figure 7-23 is representative of status display page formatting that could be used by the pilot for replying to the data link redirect.

7.3.8 Pitch, Roll, and Throttle Commands

The IFTC system generates steering commands to the flight plan identified as active by the * on the NAV SELECT page. Pitch and bank steering commands are displayed on the EADI or ADI by vertical and horizontal movements of the pitch and bank steering pointers. A pitch-up command is indicated by displacing the pitch needle from center to a position above the aircraft symbol. A bank right command is indicated by displacing the bank needle from center to a position to the right of the miniature aircraft. When the commands are tracked, the steering pointers are centered on the aircraft symbol. Continuous flight with the steering pointers centered will result in capture or maintaining capture of the horizontal and vertical portions of the desired trajectory.

Throttle position commands are displayed on the EADI as vertical movements of a "thermometer column" on the left wing of the airplane. A command for increased speed is indicated by the upward extension of the column. Decreased



REPRESENTATIVE DATA-LINK REDIRECT RESPONSE PAGE
FIGURE 7-23

speed is commanded when the column is below the wing. This symbol disappears from view when the command is satisfied. Throttle position commands on the ADI are displayed by the glide slope indicator.

7.3.9 Automatic/Manual Flight Control Selection

Lateral, vertical, throttle, altitude, mach, and airspeed commands and path error displays are in view continuously during IFTC operation. The system may be flown either fully automatic or manually to follow the commands. This is accomplished by pressing the autothrottle (A/T) switch on the throttle and the autoflight (A/T) switch on the control stick.

Autothrottle operation is indicated by illumination of the autothrottle annunciator. Automatic pitch and bank steering is annunciated by illumination of the autoflight annunciator.

The automatic pitch and roll control system is equipped with a manual override that allows the pilot to "take over" at any time simply by applying force to the control stick. Flight directors and throttle commands will continue to display the commands necessary to return to the path. The TSD will show the relationship of the aircraft to the path. A line on the TSD (capture path) emanates from the aircraft symbol and shows the most direct, curved-path trajectory the aircraft will fly between its present position and the next waypoint if the pilot allows the automatic system to assume control at that time. This path predictor is updated every three seconds. It relieves the pilot of the need to perform relative navigation between his present position and the original path, and provides the information necessary to return to the original flight plan following any manual deviation.

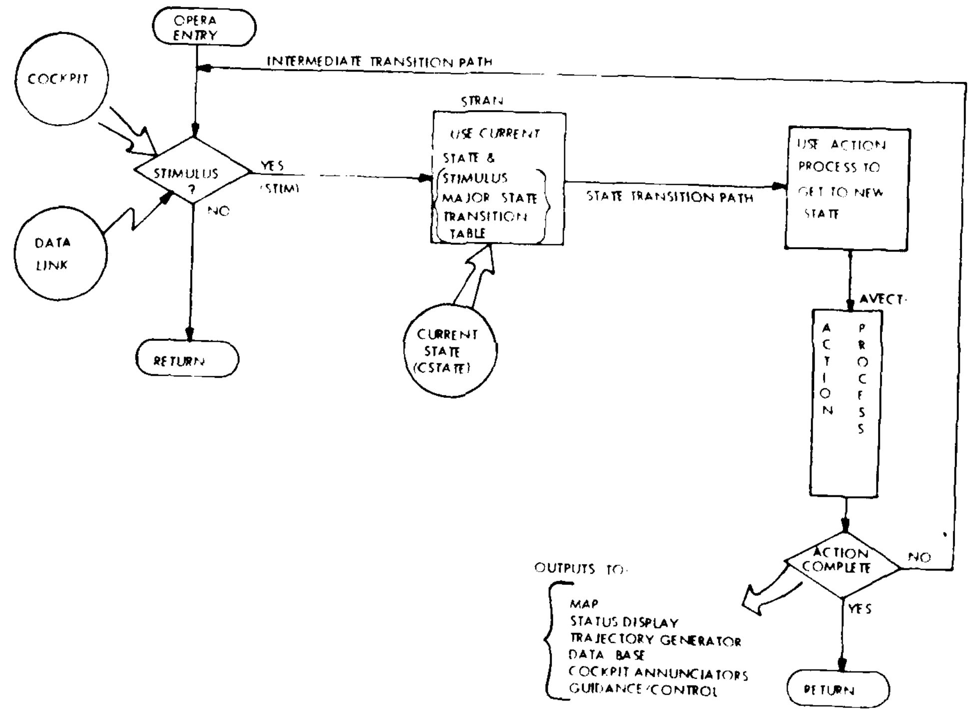
7.4 CONTROL AND DISPLAY DESIGN PHILOSOPHY

The control and display functions provide the simulation with the capability of managing the data flow between the cockpit controls and displays and the hybrid simulation computers. In particular, large quantities of digital data are processed for the status display, keyboard, and X-hair controller, and lesser amounts of discrete data are processed for the cockpit switches and annunciators. Pilot or data link-initiated changes to the mission data must be handled in an orderly manner, and the control and displays must respond to mode and control actions taken by the pilot through the status display keyboard, flight mode keyboard, TSD mode controller, and switches associated with the throttle and control stick.

Because of the compexity of the data handling and display problem, and a strong desire to have the control and display design lend itself to a straightforward procedure for making changes, it was decided to use finite automata theory in the control and display design. As a result the control and display processing is table driven.

Two types of tables are utilized in the design, the Major State Transition table and the Intermediate Transition tables. Figure 7-24 illustrates in a simplified fashion the logic flow among the major control/display processing functions.

The controlling subroutine, OPERA, is called by the executive program each 333 1/3 milliseconds (3 Hz rate). If no stimulus has been detected since the last call, program control returns to the executive. A stimulus may occur as



CONTROL/DISPLAY PROCESSING
FIGURE 7-24

a result of a cockpit action or a data link transmission. A third source of stimuli -- those which are internally generated -- is possible.

The current system state is a stable state in that in the absence of any further stimuli the system will remain in that state. When a stimulus is received, the current system state (before receipt of the stimulus) and the stimulus code are used as entries into the Major State Transition table. (Table D-I, Appendix D)

The intersection of the current state and the stimulus is the next state code and the action process to get there. The next state code will identify either another stable state or an intermediate transition state (MTR). The intermediate transition state is an unstable state and requires at least one additional pass through the appropriate action process to arrive at a stable state. Table D-II in Appendix D identifies the MTRs. Generally, as a function of an index value, the MTR tables will specify either another MTR state or stable state and the action process required to reach that state. When a stable state is reached, the processing stops until another stimulus is received and the entire process is repeated.

The action processes will generally involve system processing which will, in turn, affect the cockpit TSD, the status display, the trajectory generator, the flight data base, the cockpit annunciators, and the guidance and control functions.

Flow diagrams for OPERA, the operations control program, and STAGEN, the status display refresh program, are shown in Figures D-1 and D-2, in Appendix D.

The Machine State Diagrams, which pictorially describe the actions required to transition from one stable state to the next, are included in Appendix D. Figure D-3 is a sample, complete with annotations to aid the reader's understanding, and Figures D-4 to D-18 are the actual diagrams.

8 JTIDS SIMULATION

"The Joint Tactical Information Distribution System (JTIDS) is a digital data bus, disseminating tactical information. The data bus is a line-of-sight communication system which has extended range capability enabled by means of relaying. JTIDS is a secure system utilizing spread spectrum techniques, operating in the TACAN frequency band. Data transmissions are time-slotted (TDMA) and referenced to a master user, who can be any a priori defined user. Acquisition of the net time reference is accomplished by a passive search and track process, prior to being given the freedom to actively participate in the net. Once a user has achieved synchronization, it can begin transmitting in its assigned time slot." [1]

The types of allowable transmissions are fixed by a message catalog. These message types are listed, defined, and clarified by example in ref. [1], and include such types as emergency warning to aircrew; urgent message receipt; and advisory data.

JTIDS is intended to provide needed tactical information such as positions and velocities of targets, hostile aircraft, SAMS, and friendly forces to friendly aircrews, force commanders, and other users. It is to be secure and jam-resistant.

The operational possibilities of the integration of the JTIDS-like data-link system with the IFTC system have been discussed in Sections 2.1 and 2.2 and in Section 3.

The purpose of this section is to discuss the mechanics of the incorporation of the JTIDS information input into the simulation. The IFTC program was not concerned with simulating the JTIDS transmission and net characteristics, per se. It was concerned, however, with demonstrating the response of the IFTC system to certain classes of simulated JTIDS inputs. No sorting of the inputs by priority was performed, and it was assumed that if the JTIDS information reached the simulated airborne computer, it had been filtered, and judged to be of sufficiently high priority to be processed immediately.

The purpose of the JTIDS simulation was twofold:

- Demonstrate the advantages afforded by an on-board trajectory generator which can immediately react to data-link inputs.

- Demonstrate that without an on-board system that can automatically react to data-link inputs, the pilot will likely be overwhelmed by the available data.

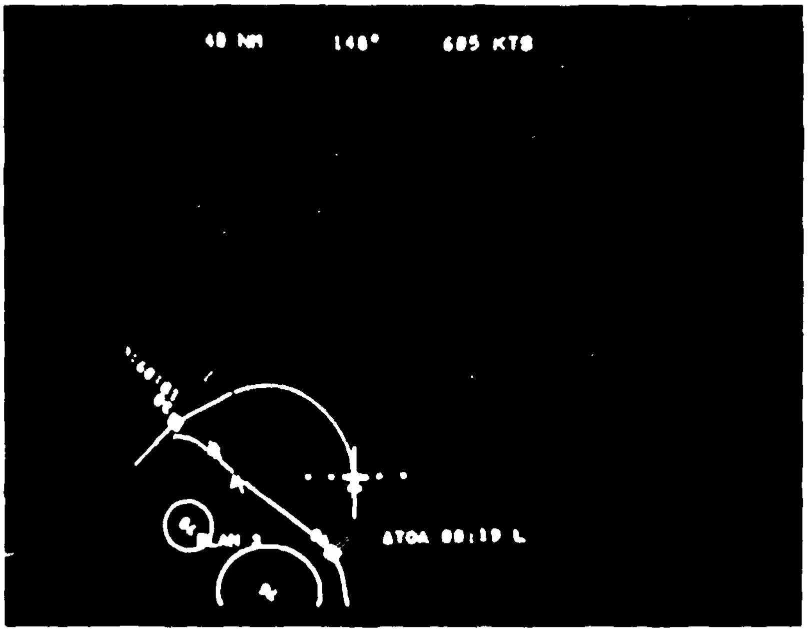
As described in Sections 2 and 3, the IFTC system can accept data-link inputs which may be as simple as the coordinates of a target-of-opportunity or as complex as a series of ordered points comprising an entire mission redirect, and with a critical time-of-arrival assigned at one or more key points. The data-link inputs may also be the positions and other information such as type, direction of flight and number of hostile and friendly bogies. The inputs may also be the positions and types of SAM or AAA emplacements.

The IFTC system reacts by first warning the pilot that a data-link input has been received. This is accomplished by illuminating the DATA-LINK annunciator on the glare shield. This action serves to attract the pilot's attention and cue him to inspect the TSD and the status display. Additional information is always provided on either or both of these displays.

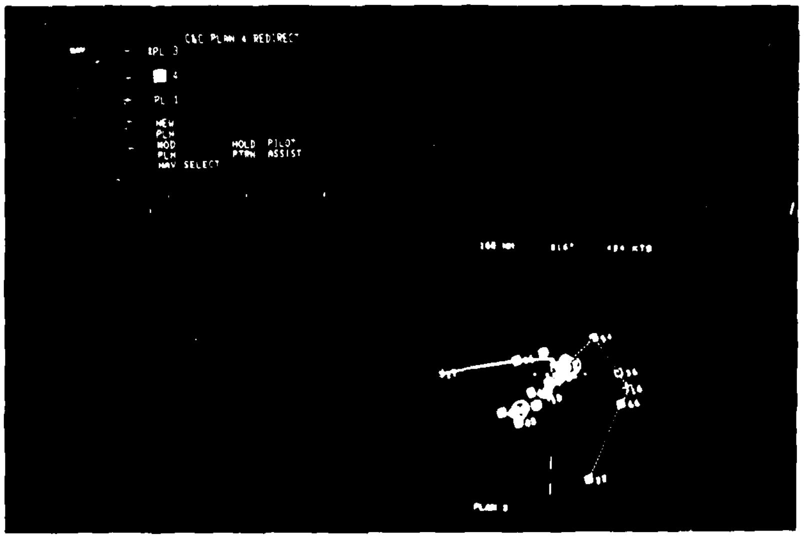
For the case of a hostile bogey warning, the IFTC system responds immediately by placing the bogey symbols on the TSD as shown in Figure 8-1. If updated bogey position information is available, the symbols will appear to move across the TSD. The bogey symbols are blinked to cause them to "stand-out" on the display. If the pilot reacts to the bogies by assuming manual control and deviating from the nominal flight plan, the system responds by creating a "capture" profile from the aircraft position to the next point in the mission list.

As the pilot continues to deviate, the "capture" profile is recomputed and redrawn on the TSD to always show the pilot the most direct route back to the original mission plan. Each time this flight segment is recomputed, the times-of-arrival and fuel estimates for all the remaining points in the mission are updated. This "capture" profile is also shown in Figure 8-1.

For a mission redirect, more cues are given. The IFTC system accepts the redirect waypoints, times-of-arrival, etc., and constructs a flyable trajectory through the points including a "link" segment from the aircraft to the first point in the redirect mission. This trajectory is immediately displayed on the TSD in dashed format as shown in Figure 8-2. Notice in the figure that the DATA LINK light is illuminated.



DATA-LINKED POSITIONS OF HOSTILE BOGIES AND CAPTURE
TRAJECTORY FOLLOWING AVOIDANCE MANEUVER
FIGURE 8-1

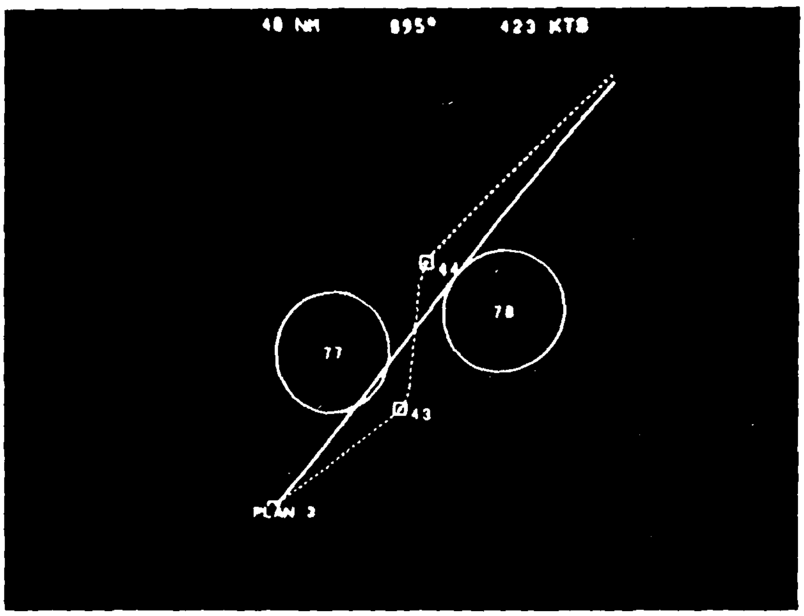


MISSION REDIRECT PROFILE
FIGURE 8-2

In addition to the new profile on the map, the status display is displaying the message: "C&C PLAN 4 REDIRECT." This indicates to the pilot that he has been given a mission redirect. The redirect has been assigned as PLAN 4, and the NAV SELect page has been automatically placed on the status display for either rapid engagement of the redirect or rapid access to the data for the redirect.

Another class of information included in the data-link simulation was the location and lethal envelope size of SAM threats. An example of the TSD display of the threats and the avoidance profile through them is shown in Figure 8-3.

The trajectory generator has automatically recognized the violation of the lethal envelopes by the nominal trajectory, and constructed a modified profile to clear the threats, as shown by the dashed line profile.



DATA-LINKED SAM THREATS
FIGURE 8-3

The simulation has the following data-linked capabilities:

2 - friendly aircraft - fighter type

2 - tanker aircraft; one in standard racetrack refuel pattern; one in direct track pattern

4 - hostile aircraft - fighter type

6 - data-linked missions of multiple waypoints and targets

10 - SAM or AAA threats of varying threat envelope size

The data for all data-linked inputs were specified during the simulation initialization. At the appropriate times during the mission execution, the data-link inputs were activated by entering a code number on the hybrid control console, which served as the experimenters' station as described in Section 4.

In addition to these capabilities, it was also possible to simulate the effects of either a data-linked or radar update of target coordinates.

The automatic response of the IFTC system to the data-linked inputs was contrasted to the alternative approach for attempting to respond to something as dynamic and complex as a mission redirect. The alternate approach would be to require the pilot to manually insert the coordinates of all the redirect mission points into the airborne computer, a time-consuming and error-prone procedure.

In the total absence of an IFTC-type system, the pilot is forced to use maps, kneepads and whatever other resources are at his disposal to attempt to construct a flight plan and perform time-of-arrival and fuel usage estimates, a task felt to be impossible in the opinion of the pilot test subjects used during pilot testing.

9 SYSTEM SIMULATOR

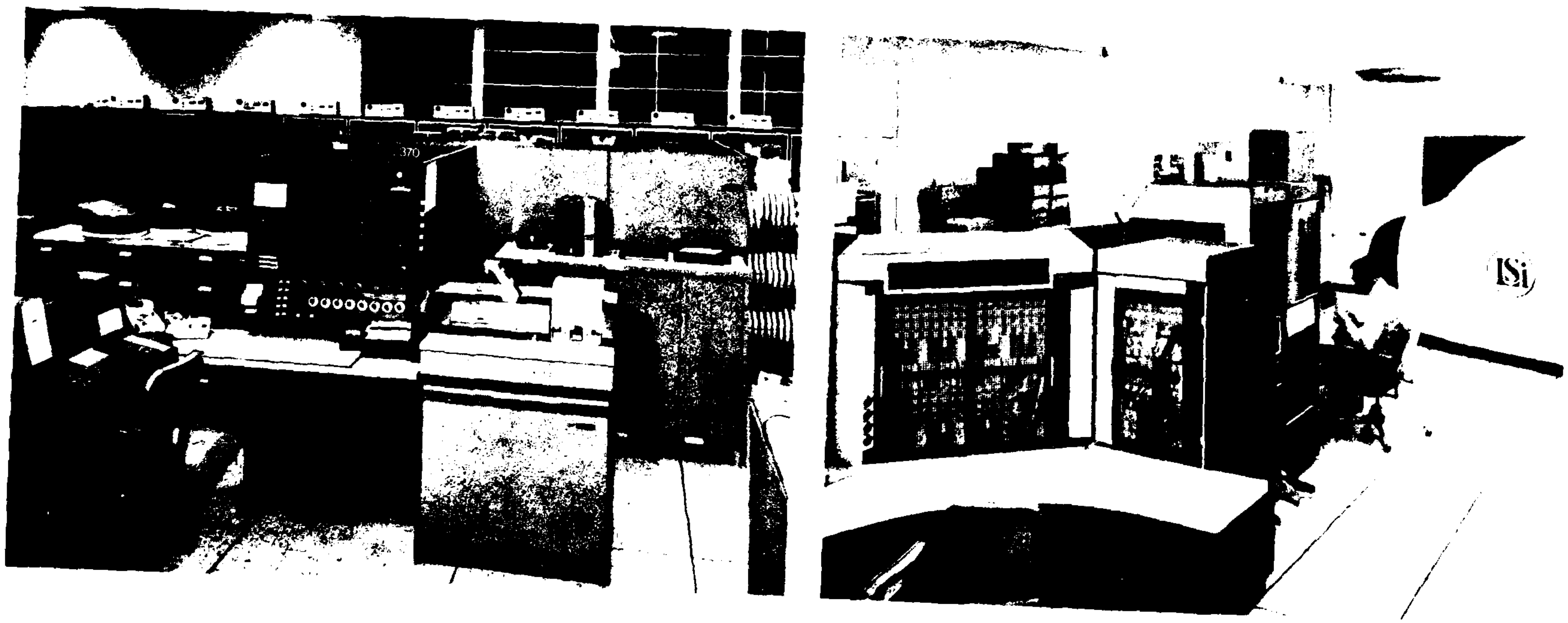
9.1 GENERAL DESCRIPTION

A hybrid simulation was developed to demonstrate the Integrated Flight Trajectory Control concept. The simulation includes a cockpit in which were installed the controls and displays. All processing is accomplished in real time which allows the simulation to be exercised by a "pilot" in the cockpit. The simulation was performed in the LSI Hybrid Computing Facility, Figure 9-1, and was used to demonstrate the concepts as described in Sections 1.3 and 3.0, and pilot testing as described in Section 4.0.

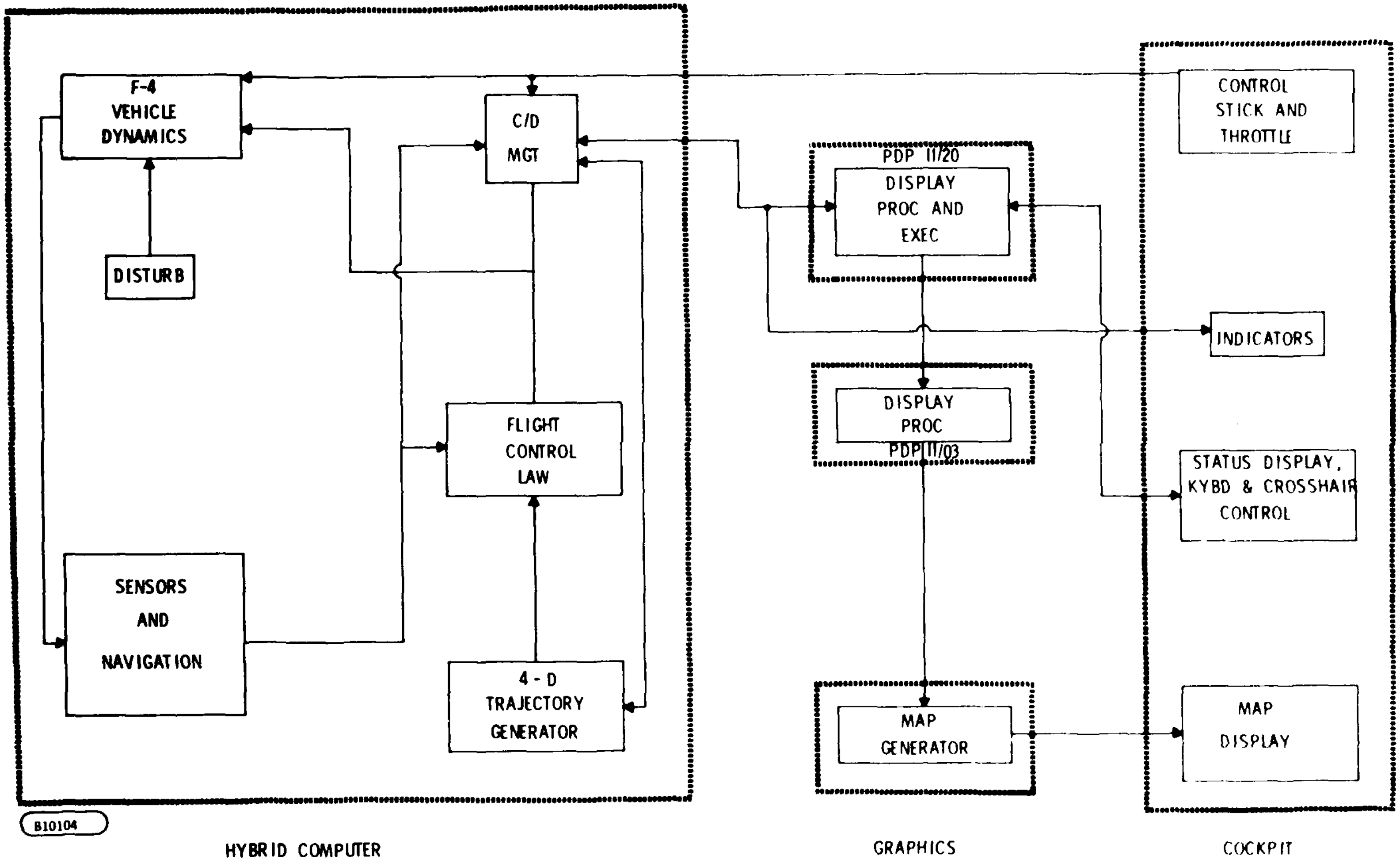
9.2 SIMULATION CONFIGURATION

The simulation configuration, Figure 9-2, shows the informational flow among the various functions. The following computers were involved in the simulation:

- Applied Dynamics Model AD/4 Hybrid Computer which has digital logic capability, 16 analog-to-digital converters, 16 sense and control lines, and 108 digitally set coefficient devices, in addition to the usual analog computing elements.
- Applied Dynamics Model AD/256 Analog Computer with full trunking to the AD/4.
- Digital Equipment Corporation (DEC) PDP 11, Model 20 digital computer with magnetic tape and disc memory units.
- Digital Equipment Corporation PDP 11, Model 03 minicomputer.
- IBM 370 Model 155 digital computer with associated hardware. The 370/155 is interfaced with the AD/4 and the PDP 11/20 via the hybrid interface (HIF) and the remote interface (RIF).
- Hughes Conographic electronic symbol generation graphics system.
- Single-seat, tactical fighter cockpit with associated controls, displays, and analog and digital interfacing to the simulation computers. The cockpit interfacing also includes the read/write buffer memory and character generation electronics for the status display.



LSI HYBRID COMPUTING FACILITY
FIGURE 9-1



SIMULATION ORGANIZATION
FIGURE 9-2

9.3 COMPUTER FUNCTIONS

The vehicle dynamics consist of a six-degree-of-freedom model of the F-4E aircraft dynamics. The model is a combination digital/analog mechanization, as described in Appendix A. The four-dimensional guidance and control laws, and profile generation are computed in the IBM 370. Guidance and control is described in Section 6 and the trajectory generation is described in Section 5.

In addition, the control and display management, as described in Section 7, is processed in the IBM 370. The cockpit button pushing activity, however, is monitored by the PDP 11/20. This information is passed to the IBM 370 via the hybrid digital data lines. The status display pages formatting information (everything but data) is stored on the 11/20 disc system. The digital data for the pages is supplied by the IBM 370 via the same digital data lines, and is overlaid on the format information.

The IBM 370 is also used to pass TSD trajectory information to the 11/20. This information is in engineering units and is unusable by the Conographic System in that form. The 11/20 passes the data to the 11/03 which converts the trajectory information to the parametric form acceptable to the Conographic System.

The IBM 370 also computes those quantities needed for driving the conventional cockpit displays of airspeed, mach, altitude, vertical rate, fuel remaining, and the ADI symbology. The digital outputs are converted to analog and scaled properly for each instrument. In some instances further signal conversion from DC to synchro-type format is required. The outputs of the control stick, throttle, gear, and speed brakes are passed to the computers from the cockpit. Throttle positioning commands are sent to the cockpit during automatic throttle mode operation.

A separate video cable interfaces the video information from the Conograph system to the TSD monitor in the cockpit. An analog interface couples the output of the throttle-mounted crosshair controller to the PDP 11/20. In Figure 9-2 the large box labeled "hybrid computer" represents the combination of the IBM 370 and the Applied Dynamics AD-4.

10 WEAPON DELIVERY

10.1 WEAPON DELIVERY OPERATIONAL CAPABILITY

To provide weapon delivery capability, the blind mode weapon delivery algorithms from the Air Force AN/ARN-101 Digital Modular Avionics System were incorporated in the IFTC simulation.

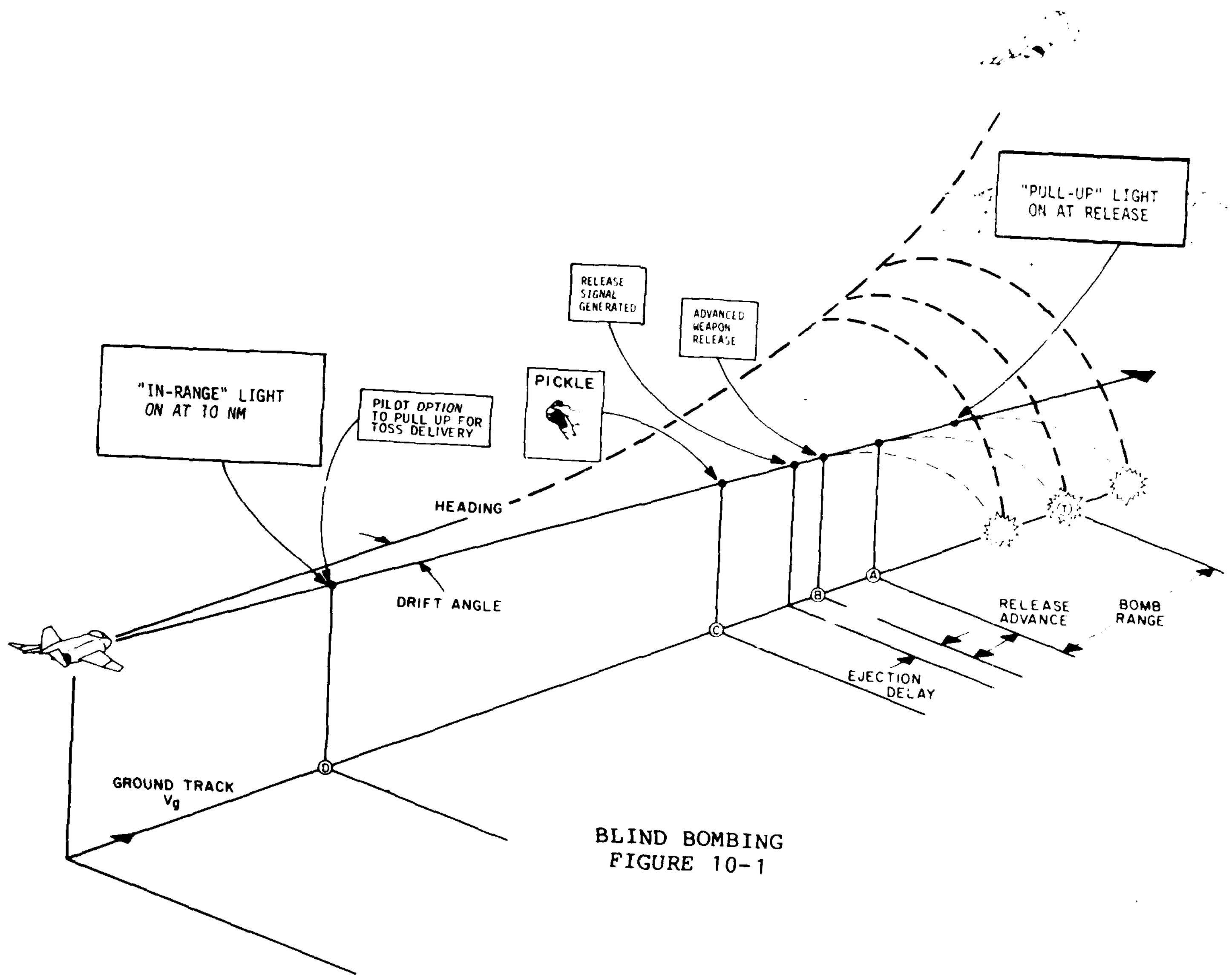
The guidance and control philosophy for implementing the weapon delivery was to have the IFTC steering functions control the aircraft to the IP point. At the IP, steering control is smoothly passed to the ARN-101 blind weapon delivery steering functions. The ARN-101 steering functions control the aircraft until weapon release is detected, at which time the IFTC trajectory generator creates a "capture" trajectory from the aircraft position at weapon release to the egress point. This capture trajectory is linked to the remainder of the mission, and all fuel estimates and times-of-arrival are updated.

This control philosophy allows the substitution of other weapon delivery algorithms, such as curved path or conventional visual modes, with minimal impact on the simulation structure.

Figure 10-1 illustrates the blind weapon delivery geometry and the events sequence for a typical run-in to the target. Upon target approach, the "In-Range" annunciator on the glare shield illuminates at the range at which a pullup maneuver may be initiated for a maximum standoff range, toss delivery. A normal level laydown maneuver may be continued, however, or any desired vertical path maneuver may be made. Automatic release will deliver the bomb provided the release consent switch (pickle) is maintained depressed.

During the delivery maneuver, after the "In-Range" illuminates, the roll steering command is based initially on an anticipated toss maneuver, but gradually shifts to the laydown maneuver if no pullup occurs. The roll command will then follow and use any pullup or dive maneuver.

Also, after the "In-Range" illumination, the EADI (or ADI) horizontal pointer will indicate a dive angle which will result in weapon release at approximately the break altitude, if followed.



BLIND BOMBING
FIGURE 10-1

10.2 BALLISTICS AND RELEASE PREDICTION

The simulation used the external ballistics of an MK-82 GP bomb. The solution to the weapon delivery problem is based on two sets of computations:

1. Aircraft state prediction at the time of weapon release

2. An accurate model of the external weapon ballistics

The aircraft state prediction algorithm estimates the aircraft position and velocity vectors at the time of release based on predicted aircraft accelerations. The predicted time to release is continuously adjusted by comparison of the current range to target with the predicted aircraft distance to release, plus the ballistic range.

The computation of the Mark 82 bomb range and time of fall is accomplished by numerical integration of the exterior ballistics. The ARN-101 technique is well suited for high-speed, airborne digital computers and is applicable to the various classes of unguided air-to-ground weapons. The computations require the inputs of altitude and velocity at release, the ballistics coefficients, and an atmospheric model of density and wind.

The technique uses a time-base, second-order, Runge-Kutta numerical integration process with a fixed number of time (integration) steps for all weapons. The number of integration steps is kept small and fixed to ensure that calculation time is small and fixed. This is an important requirement for airborne use and extensive experience with this technique has shown that good accuracy is maintained for all classes of weapons.

The equations of motion are developed assuming the projectile to be a point mass, acted upon only by the forces of gravity, wind and air mass resistance. The assumptions are:

a. Flat, non-rotating Earth
b. Gravitational attraction is constant
c. The projectile is a point mass
d. The projectile is constant mass and non-powered

With these assumptions, the following differential equations apply:

$$\frac{d^2x}{dt^2} + H\frac{dx}{dt} = 0$$

$$\frac{d^2y}{dt^2} + H\frac{dy}{dt} + G = 0 \qquad \text{Eq. 10-1}$$

$$\frac{d^2z}{dt^2} + H\frac{dz}{dt} = 0$$

where

x = Down range
y = Altitude
z = Cross range
t = Time
G = Gravitational attraction
H = Drag function

The drag function, H, is computed as

$$H = \frac{\rho}{W} d^2 \frac{\Pi}{8} C_D V \qquad \text{Eq. 10-2}$$

where

ρ = atmospheric mass density
W = bomb mass
d = bomb diameter
C_D = weapon coefficient of drag
V = velocity of weapon in air mass

The atmospheric density, ρ, will be determined from a table of the pressure and temperature values. The parameter, C_D, is empirically derived and given in tabular form as a function of Mach number for the Mark 82 bomb, a typical low drag bomb. The behavior of C_D with Mach number is in a form easily used by the computer for the impact range computation. This approach to weapon delivery is very [illegible] and easily adaptable to the addition of a new [illegible] inventory.

Defining three new variables, V_x, V_y, and V_z as,

$$\frac{dx}{dt} = V_x$$

$$\frac{dy}{dt} = V_y \qquad \text{Eq. 10-3}$$

$$\frac{dz}{dt} = V_z$$

Substituting the above expressions in Equation 10-1 result in,

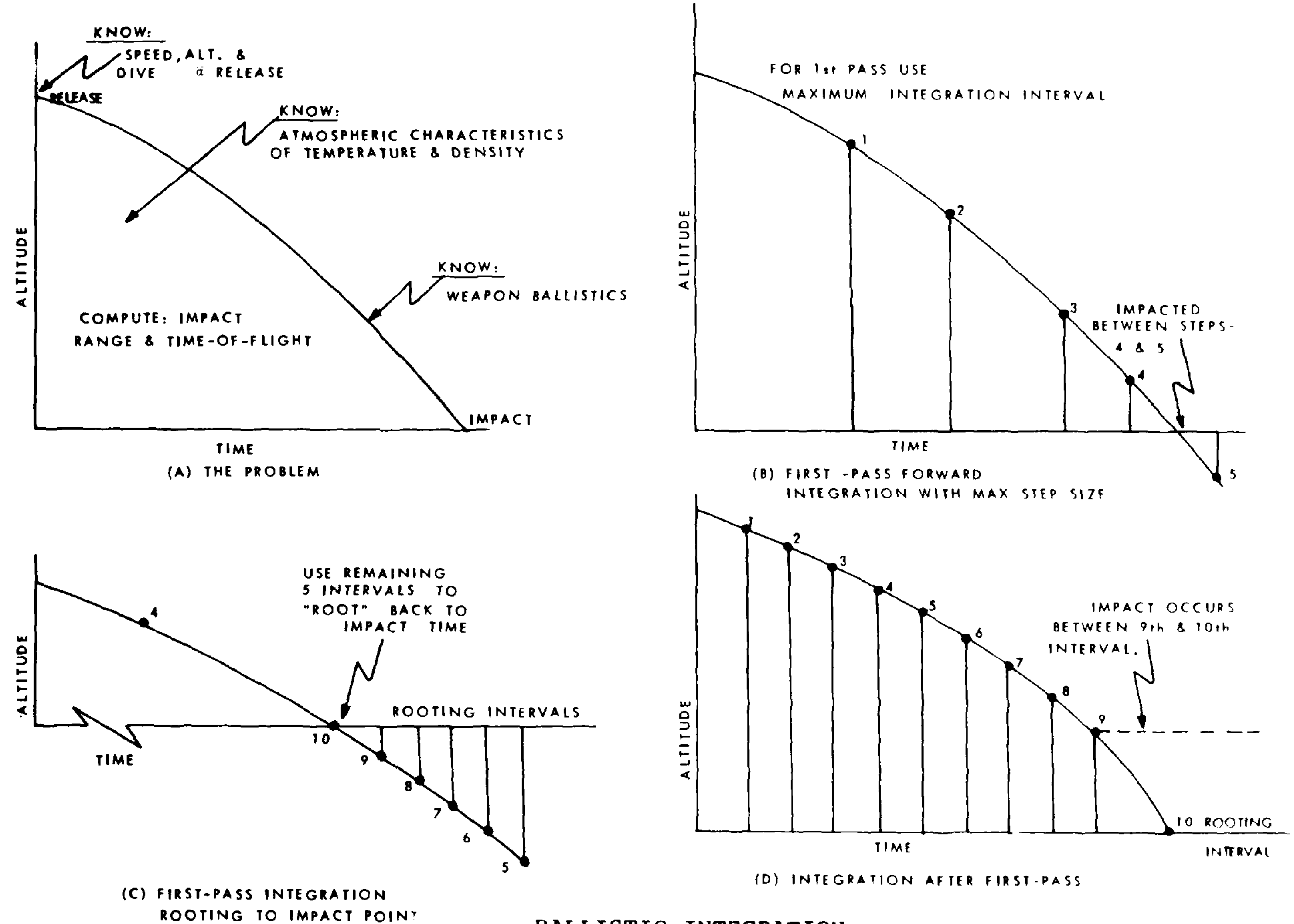
$$\frac{dV_x}{dt} = -HV_x$$

$$\frac{dV_y}{dt} = -HV_y - G \qquad \text{Eq. 10-4}$$

$$\frac{dV_z}{dt} = -HV_z$$

The six first-order differential Equations 10-3 and 10-4 are the desired equations with time as the independent variable. The Runge-Kutta integration technique provides a step-by-step method of yielding dependent variable values at given intervals of the independent variable.

The total weapon trajectory is divided into 10 units and within each unit it is assumed that all forces remain constant. The assumption of constant forces permits the determination of the projectile position and velocity at the end of the unit. The forces are recomputed on the basis of the updated position and velocity and these forces are used by the computations for the next unit. The process is repeated until all units are completed. The initial integration attempt and integration interval adjustments are illustrated in Figure 10-2. For a complete discussion and definition of the process, see reference (4).



BALLISTIC INTEGRATION
FIGURE 10-2

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APPENDIX A

F-4E SIX-DEGREE-OF-FREEDOM A/C MODEL

APPENDIX A

F-4E SIX-DEGREE-OF-FREEDOM A/C MODEL

A.1 AIRCRAFT MODEL

The F-4E aircraft was modeled for use in the IFTC dynamic simulation. The standard non-linear six-degree-of-freedom flight equations were used to define aircraft motion. Very few simplifying assumptions were made. The aircraft bending modes and ground and jet effects were neglected, and both engines were assumed to operate at the same thrust values.

A.2 EQUATIONS OF MOTION

The equations of motion of an airframe referred to Eulerian axes are:

$$\begin{bmatrix} \dot{U} \\ \dot{V} \\ \dot{W} \end{bmatrix} = \frac{1}{m} \begin{bmatrix} \Sigma F_x \\ \Sigma F_y \\ \Sigma F_z \end{bmatrix} + \begin{bmatrix} 0 & R & -Q \\ -R & 0 & P \\ Q & -P & 0 \end{bmatrix} \begin{bmatrix} U \\ V \\ W \end{bmatrix}$$

$$\begin{bmatrix} \dot{P} \\ \dot{Q} \\ \dot{R} \end{bmatrix} = \begin{bmatrix} I_{XX} & 0 & -I_{XZ} \\ 0 & I_{YY} & 0 \\ -I_{XZ} & 0 & I_{ZZ} \end{bmatrix}^{-1} \left\{ \begin{bmatrix} \Sigma L \\ \Sigma M \\ \Sigma N \end{bmatrix} + \begin{bmatrix} 0 & R & -Q \\ -R & 0 & P \\ Q & -P & 0 \end{bmatrix} \begin{bmatrix} I_{XX} & 0 & -I_{XZ} \\ 0 & I_{YY} & 0 \\ -I_{XZ} & 0 & I_{ZZ} \end{bmatrix} \begin{bmatrix} P \\ Q \\ R \end{bmatrix} \right\}$$

$$= \begin{bmatrix} (I_1 R + I_2 P)Q + I_3 \Sigma L + I_4 \Sigma N \\ I_5 RP + I_6 (R^2 - P^2) + I_7 \Sigma M \\ (I_8 P + I_9 R)Q + I_4 \Sigma L + I_{10} \Sigma N \end{bmatrix}$$

where

$$I_1 = \frac{(I_{yy} - I_{zz}) I_{zz} - I_{xz}^2}{I_{xx} I_{zz} - I_{xz}^2} \qquad I_2 = \frac{(I_{xx} - I_{yy} + I_{zz}) I_{xz}}{I_{xx} I_{zz} - I_{xz}^2}$$

$$I_3 = \frac{I_{zz}}{I_{xx}I_{zz}-I_{xz}^2} \qquad I_4 = \frac{I_{xz}}{I_{xx}I_{zz}-I_{xz}^2}$$

$$I_5 = \frac{I_{zz}-I_{xx}}{I_{yy}} \qquad I_6 = \frac{I_{xz}}{I_{xy}}$$

$$I_7 = \frac{1}{I_{yy}} \qquad I_8 = \frac{(I_{xx}-I_{yy})I_{xx}+I_{xz}^2}{I_{xx}I_{zz}-I_{xz}^2}$$

$$I_9 = \frac{(I_{yy}-I_{zz}-I_{xx})I_{xz}}{I_{xx}I_{zz}-I_{xz}^2} \qquad I_{10} = \frac{I_{xx}}{I_{xx}I_{zz}-I_{xz}^2}$$

and

m = mass of airframe

$\dot{U}, \dot{V}, \dot{W}$ = linear accelerations along aircraft body axes x, y, and z

U, V, W = linear velocities along aircraft body axes x, y, and z

$\dot{P}, \dot{Q}, \dot{R}$ = angular accelerations about aircraft body axes x, y, and z

P, Q, R = angular velocities about aircraft body axes x, y, and z

I_{xx}, I_{yy}, I_{zz} = aircraft moments of inertia

I_{xz} = aircraft product of inertia

$\Sigma F_x, \Sigma F_y, \Sigma F_z$ = external forces representing the summation of the aerodynamic, weight and thrust forces acting on the aircraft and resolved along the x, y, and z body axes

ΣL, ΣM, ΣN = external moments representing the summation of the aerodynamic and thrust moments acting on the aircraft and resolved about the x, y, and z axes

The external forces and moments acting on the aircraft consist of aerodynamic, propulsion, and gravity components.

A.2.1 GRAVITY FORCES (F_{x_G}, F_{y_G}, F_{z_G})

The forces due to gravity acting along the body axes depend on the aircraft attitude and weight,

$$F_{x_G} = -W\sin\theta$$

$$F_{y_G} = W\cos\theta\sin\phi$$

$$F_{z_G} = W\cos\theta\cos\phi$$

where

W = weight of aircraft

θ = aircraft pitch attitude

ϕ = aircraft roll attitude

A.2.2 THRUST FORCES AND MOMENTS (F_{x_T}, F_{y_T}, M_T)

In order to determine the engine thrust terms, it is necessary to define the relationship between the thrust vector and the aircraft axis system. The C.G. must be known to determine moments due to thrust, and the angles between the thrust vector and the aircraft body axes must be known in order to resolve the thrust along the body axes. The angle between the thrust vector and the aircraft horizontal plane is 5.25° and the angle is 0.25° in the vertical plane. The thrust line acting through the Water Line is 313.5" and the thrust line acting through the Buttock Line is 32.405". The F-4E is equipped with two engines. For this simulation, both engines are assumed to operate at the same thrust. The components of force due to thrust are,

$$F_{x_T} = (T_1 + T_2)\cos 5.25° \cos 0.25° \approx 2T$$

$$F_{z_T} = (T_1 + T_2)\cos 0.25° \sin 5.25° = -.183T$$

and the pitching moment due to thrust is

$$M_T = (T_1 + T_2)\left[(\cos 5.25° \cos 0.25°)(z_{CG} \quad 32.405'') + \cos 0.25° \sin(5.25°)(x_{CG} - 313.5)\right]/12''$$

or

$$M_T \approx 2T\left[(z_{CG} - 32.405'') + .0916(x_{CG} - 313.5)\right]/12''$$

where x_{CG} and z_{CG} are the C.G. locations along the x and z body axis, respectively.

A.2.3 AERODYNAMIC FORCES AND MOMENTS (F_{x_A}, F_{y_A}, F_{z_A}, L_A, M_A, N_A)

The aerodynamic forces and moments are,

$$F_{x_A} = -qS\Sigma C_D \qquad L_A = qSb\Sigma C_l$$

$$F_{y_A} = qS\Sigma C_y \qquad M_A = qS\bar{c}\Sigma C_m$$

$$F_{z_A} = -qS\Sigma C_L \qquad N_A = qSb\Sigma C_n$$

where

q = dynamic pressure

b = wing span = 38.67 ft.

$\bar{c}$ = mean aerodynamic chord = 16.04 ft.

S = wing area = 530 ft.^{2}

The F-4E aircraft is capable of flying in a clean or high lift configuration. The high lift configuration defined consists of the three leading edge flaps (inboard, center, outboard) deflected 30°, 60°, 60° (respectively), the trailing edge flap deflected 60°, and the landing gear extended. The expanded aero coefficients for the clean aircraft are,

$$\Sigma C_D = C_D(M, C_L) + \Delta C_{D_{\delta_{sb}}}(M, C_L, \delta_{sb})$$

$$\Sigma C_Y = C_{Y_\beta}(M, h, \alpha_w)\beta + \left(\frac{b}{2U_s}\right) C_{Y_r}(M, h, \alpha_w)R_s + \left(\frac{b}{2U_s}\right) C_{Y_p}(M, h, \alpha_w)P_s$$

$$+ C_{Y_{\delta_a}}(M)\delta_a + C_{Y_{\delta_{sp}}}(M)\delta_{sp} + C_{Y_{\delta_r}}(M, h)\delta_r$$

$$\Sigma C_L = C_L(M, h, \alpha_w) - \left(\frac{\bar{c}}{2U_s}\right) C_{Z_q}(M, h)Q_s - \left(\frac{\bar{c}}{2U_s}\right) C_{Z_{\dot{\alpha}}}(M, h,)\dot{\alpha}$$

$$+ C_{L_{\delta_s}}(M, h, \alpha_w)\delta_s + C_{L_{\delta_{sp}}}(M, h)\delta_{sp} + C_{L_{\delta_a}}(M, h)\delta_a + C_{L_{\delta_{sb}}}(M, \alpha_w)\delta_{sb}$$

$$\Sigma C_l = C_{l_\beta}(M, h, \alpha_w)\beta + \left(\frac{b}{2U_s}\right) C_{l_r}(M, h, \alpha_w)R_s + \left(\frac{b}{2U_s}\right) C_{l_p}(M, h, \alpha_w)P_s$$

$$+ C_{l_{\delta_{sp}}}(M, h, \alpha_w)\delta_{sp} + C_{l_{\delta_a}}(M, h, \alpha_w)\delta_a + C_{l_{\delta_r}}(M, h, \alpha_w)\delta_r$$

$$\Sigma C_m = C_m(M, h, \alpha_w) + \left(\frac{\bar{c}}{2U_s}\right) C_{m_q}(M, h)Q_s + \left(\frac{\bar{c}}{2U_s}\right) C_{m_{\dot{\alpha}}}(M, h)\dot{\alpha}$$

$$+ C_{m_{\delta_s}}(M, h, \alpha_w)\delta_s + C_{m_{\delta_{sp}}}(M, h, \alpha_w)\delta_{sp} + C_{m_{\delta_a}}(M, h, \alpha_w)\delta_a + C_{m_{\delta_{sb}}}(M, \alpha_w)\delta_{sb}$$

$$\Sigma C_n = C_{n_\beta}(M, h, \alpha_w)\beta + \left(\frac{b}{2U_s}\right) C_{n_r}(M, h, \alpha_w)R_s + \left(\frac{b}{2U_s}\right) C_{n_p}(M, h, \alpha_w)P_s$$

$$+ C_{n_{\delta_{sp}}}(M, h, \alpha_w)\delta_{sp} + C_{n_{\delta_a}}(M, h, \alpha_w)\delta_a + C_{n_{\delta_r}}(M, h)\delta_r$$

and the expanded aero coefficients for the high lift configured aircraft are,

$$\Sigma C_D = C_D(C_L,\ \delta_s,\ C_\mu) + \Delta C_{D_{\delta_{sb}}}(M,\ C_L,\ \delta_{sb})$$

$$\Sigma C_y = C_{y_\beta}(\alpha_w)\beta + \left(\frac{b}{2U_s}\right)C_{y_r}(\alpha_w)R_s + \left(\frac{b}{2U_s}\right)C_{y_p}(\alpha_w)P_s$$
$$+ C_{y_{\delta_a}}(\alpha_w)\delta_a + C_{y_{\delta_{sp}}}(M)\delta_{sp} + C_{y_{\delta_r}}(\alpha_w)\delta_r$$

$$\Sigma C_L = C_L(\alpha_w,\ \delta_s,\ C_\mu) - \left(\frac{\bar{c}}{2U_s}\right)C_{z_q}(\alpha_w)Q_s - \left(\frac{\bar{c}}{2U_s}\right)C_{z_{\dot{\alpha}}}(\alpha_w)\dot{\alpha}$$
$$+ C_{L_{\delta_{sp}}}(M,\ h)\delta_{sp} + C_{L_{\delta_a}}(\alpha_w)\delta_a + C_{L_{\delta_{sb}}}(M,\ \alpha_w)\delta_{sb}$$

$$\Sigma C_l = C_{l_\beta}(\alpha_w)\beta + \left(\frac{b}{2U_s}\right)C_{l_r}(\alpha_w)R_s + \left(\frac{b}{2U_s}\right)C_{l_p}(\alpha_w)P_s$$
$$+ C_{l_{\delta_{sp}}}(M,\ h,\ \alpha_w)\delta_{sp} + C_{l_{\delta_a}}(\alpha_w)\delta_a + C_{l_{\delta_r}}(\alpha_w)\delta_r$$

$$\Sigma C_m = C_m(C_L,\ \delta_s,\ C_\mu) + \left(\frac{\bar{c}}{2U_s}\right)C_{m_q}(\alpha_w)Q_s + \left(\frac{\bar{c}}{2U_s}\right)C_{m_{\dot{\alpha}}}(\alpha_w)\dot{\alpha}$$
$$+ C_{m_{\delta_{sp}}}(M,\ h,\ \alpha_w)\delta_{sp} + C_{m_{\delta_a}}(\alpha_w)\delta_a + C_{m_{\delta_{sb}}}(M,\ \alpha_w)\delta_{sb}$$

$$\Sigma C_n = C_{n_\beta}(\alpha_w)\beta + \left(\frac{b}{2U_s}\right)C_{n_r}(\alpha_w)R_s + \left(\frac{b}{2U_s}\right)C_{n_p}(\alpha_w)P_s$$
$$+ C_{n_{\delta_{sp}}}(M,\ h,\ \alpha_w)\delta_{sp} + C_{n_{\delta_a}}(\alpha_w)\delta_a + C_{n_{\delta_r}}(\alpha_w)\delta_r$$

where

U_S = stability axis velocity along x axis

P_S, R_S, Q_S = stability axes rotational velocities

β = sideslip angle

$\dot{\alpha}$ = angle of attack rate

δ_S = stabilator deflection

δ_{sp} = spoiler deflection

δ_a = aileron deflection

δ_{sb} = speed brake deflection

δ_r = rudder deflection

C_μ = leading edge boundary layer control momentum coefficient

The aerodynamic derivatives were programmed using a table lookup procedure.

The gravity and thrust forces are defined with respect to the body axis system and the aerodynamic forces and moments are defined with respect to the stability axis system. Since the equations of motion are written in the body axis system, the aerodynamic forces and moments must be transformed to the body axis.

The external forces and moments acting on the airplane and referred to the body axis coordinate system are,

$$\begin{bmatrix} \Sigma F_x \\ \Sigma F_y \\ \Sigma F_z \end{bmatrix} = \begin{bmatrix} F_{x_G} \\ F_{y_G} \\ F_{z_G} \end{bmatrix} + \begin{bmatrix} F_{x_T} \\ 0 \\ F_{z_T} \end{bmatrix} + \begin{bmatrix} \cos\alpha & 0 & -\sin\alpha \\ 0 & 1 & 0 \\ \sin\alpha & 0 & \cos\alpha \end{bmatrix} \begin{bmatrix} F_{x_A} \\ F_{y_A} \\ F_{z_A} \end{bmatrix}$$

$$= W\begin{bmatrix} -\sin\theta \\ \cos\theta\sin\phi \\ \cos\theta\cos\phi \end{bmatrix} + T\begin{bmatrix} 2 \\ 0 \\ -.183 \end{bmatrix} + \begin{bmatrix} \cos\alpha & 0 & -\sin\alpha \\ 0 & 1 & 0 \\ \sin\alpha & 0 & \cos\alpha \end{bmatrix}\begin{bmatrix} -qS\Sigma C_D \\ qS\Sigma C_y \\ -qS\Sigma C_L \end{bmatrix}$$

$$\begin{bmatrix} \Sigma L \\ \Sigma M \\ \Sigma N \end{bmatrix} = \begin{bmatrix} 0 \\ M_T \\ 0 \end{bmatrix} + \begin{bmatrix} \cos\alpha & 0 & -\sin\alpha \\ 0 & 1 & 0 \\ \sin\alpha & 0 & \cos\alpha \end{bmatrix}\begin{bmatrix} L_A \\ M_A \\ N_A \end{bmatrix}$$

$$= T\begin{bmatrix} \\ 2[(z_{CG}-32.405'') + .0916(x_{CG}-313.5'')]/12'' \\ \\ \end{bmatrix} + \begin{bmatrix} \cos\alpha & 0 & -\sin\alpha \\ 0 & 1 & 0 \\ \sin\alpha & 0 & \cos\alpha \end{bmatrix}\begin{bmatrix} qSb\Sigma C_l \\ qS\bar{c}\Sigma C_m \\ qSb\Sigma C_n \end{bmatrix}$$

with Euler angles

$$\phi = \int(P + \dot{\psi}\sin\theta)dt$$
$$\theta = \int(Q\cos\phi - R\sin\phi)dt$$
$$\psi = \int[(\dot{\phi} - P)\sin\theta + (Q\sin\phi + R\cos\phi)\cos\theta]dt$$

AD-A084 784 LEAR SIEGLER INC GRAND RAPIDS MICH INSTRUMENT DIV F/G 9/2
FEASIBILITY STUDY FOR INTEGRATED FLIGHT TRAJECTORY CONTROL (FIG--ETC(U)
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UNCLASSIFIED ID-82R-0679 AFFDL-TR-79-3123 NL

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and inertial velocities

$$V_N = U(\cos\psi\cos\theta) + V(-\sin\psi\cos\phi + \cos\psi\sin\theta\sin\phi) + W(-\sin\psi\sin\phi + \cos\psi\sin\theta\cos\phi)$$

$$V_E = U(\sin\psi\cos\theta) + V(\cos\psi\cos\phi + \sin\psi\sin\theta\sin\phi) + W(-\cos\psi\sin\phi + \sin\psi\sin\theta\cos\phi)$$

$$V_D = U(-\sin\theta) + V(\cos\theta\sin\phi) + W(\cos\theta\cos\phi).$$

With winds added the ground speed components are

$$V_{N_g} = V_N + V_W\sin\phi_W$$

$$V_{E_g} = V_E + V_W\cos\phi_W$$

and

$$V_{grd} = \sqrt{V_{N_g}^2 + V_{E_g}^2}.$$

The aircraft position in earth coordinates is

$$x = \int V_{E_g} dt$$

$$y = \int V_{N_g} dt$$

$$z = -h = \int V_d dt.$$

The air data quantities used in this simulation are

$$V_T = \sqrt{U^2 + V^2 + W^2}$$

$$\rho = \rho_0 \exp[4.35 \ln(1.-6.9E-6 \cdot h)]$$

$$a = 1117.\ \sqrt{1.-6.9E-6 \cdot h}$$

$$M = \frac{V_T}{a}$$

$$Q = \frac{1}{2} \rho V_T^2$$

$$\gamma = \tan^{-1} \frac{-V_d}{V_g}$$

$$V_{IAS} = V_T \cdot \sqrt{\rho/\rho_0}$$

where

V_T = true airspeed

ρ = air density

a = speed of sound

M = Mach number

Q = dynamic pressure

γ = flight path angle

V_{IAS} = Indicated airspeed.

The aircraft angle of attack, angle-of-attack rate, and sideslip angle are computed using the following relations:

$$\alpha = \frac{180}{\pi} \tan^{-1} (\frac{W}{U})$$

$$\alpha_W = \alpha + 1$$

$$\beta = \frac{180}{\pi} \tan^{-1} (\frac{V}{\sqrt{U^2+W^2}})$$

$$\dot{\alpha} = \frac{\dot{U}W + \dot{W}U}{U^2 + V^2}$$

where

α = angle of attack

α_W = wing angle of attack

β = side slip angle

$\dot{\alpha}$ = angle of attack rate.

Engine thrust (T) lags the commanded thrust (T_{COM}) according to

$$\dot{T} = 5.(T_{COM} - T)$$

where thrust rate is limited such that

$$|\dot{T}| \le 1835.[1.-.0125(h/1000.)]\text{lb/sec.}$$

Commanded thrust is a function of Mach (M), altitude (h), and throttle position (δ_t).

$$T_{COM} = [700. + (179.-45M)\delta_t][1.-.0125(h/1000.)] \qquad 0 \le \delta_t \le 50\%$$
$$= [9650.-2250.M + (137. + 45.M)(\delta_t - 50.)] \qquad 50\% < \delta_t \le 100\%$$
$$[1. - .0125(h/1000.)]$$

Stabilator, spoiler, aileron and rudder dynamics are all modeled as first order lags with rate and displacement limits on deflections.

- Stabilator: $\dot{\delta}_s = 20(\delta_{s_c} - \delta_s)$

  $-24.5°/\text{sec} \le \dot{\delta}_s \le 23.8°/\text{sec}$

  $-21.° \le \delta_s \le 7°$

- Spoiler: $\dot{\delta}_{sp} = 10.(\delta_{sp_c} - \delta_{sp})$

  $-25°/\text{sec} \le \dot{\delta}_{sp} \le 25°/\text{sec}$

  $-43° \le \delta_{sp} \le 43°$

- Ailerons: $\dot{\delta}_a = 10.(\delta_{a_c} - \delta_a)$

  $-25°/\text{sec} \le \dot{\delta}_a \le 25°/\text{sec}$

  $-30° \le \delta_a \le 30°$

- **Rudder:**

$$\dot{\delta}_R = 20.(\delta_{R_c} - \delta_R)$$

$$-25°/\text{sec} \le \dot{\delta}_R \le 25°/\text{sec}$$

$$-30° \le \delta_R \le 30°$$

APPENDIX B

STABILITY AUGMENTATION SYSTEM

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STABILITY AUGMENTATION SYSTEM

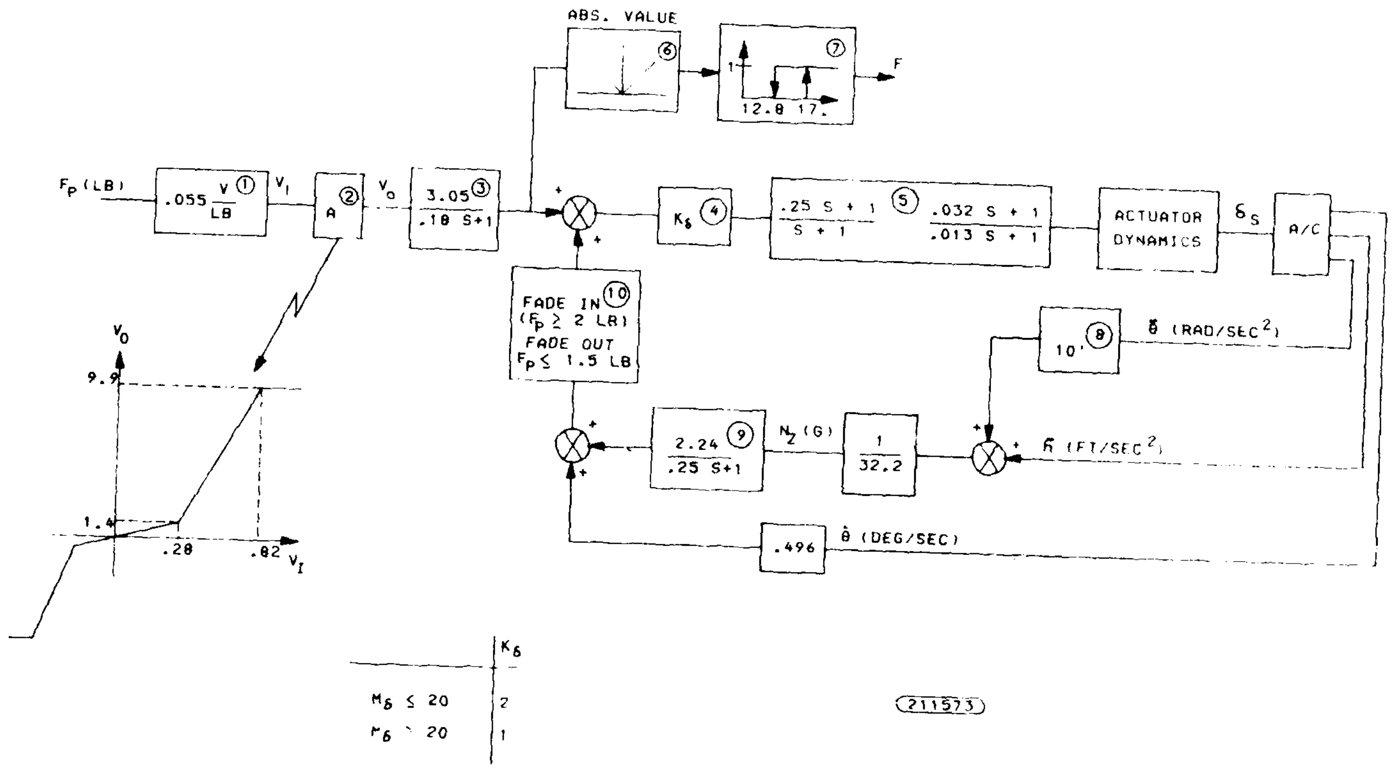
The stability augmentation system chosen for implementation on the 4D IFTC program was the Survivable Flight Control System developed by the McDonnell Douglas Corporation. The Survivable Flight Control System was designed to meet three basic handling criteria. These criteria define envelopes for the transient responses to pilot step input commands for all three aircraft axes. The C* criteria was used to define the pitch axis response, a roll rate criteria to define roll response, and the D* criteria for directional response.

C* is a normalized blend of pitch rate and normal acceleration and D* is a normalized blend of lateral acceleration and side slip.

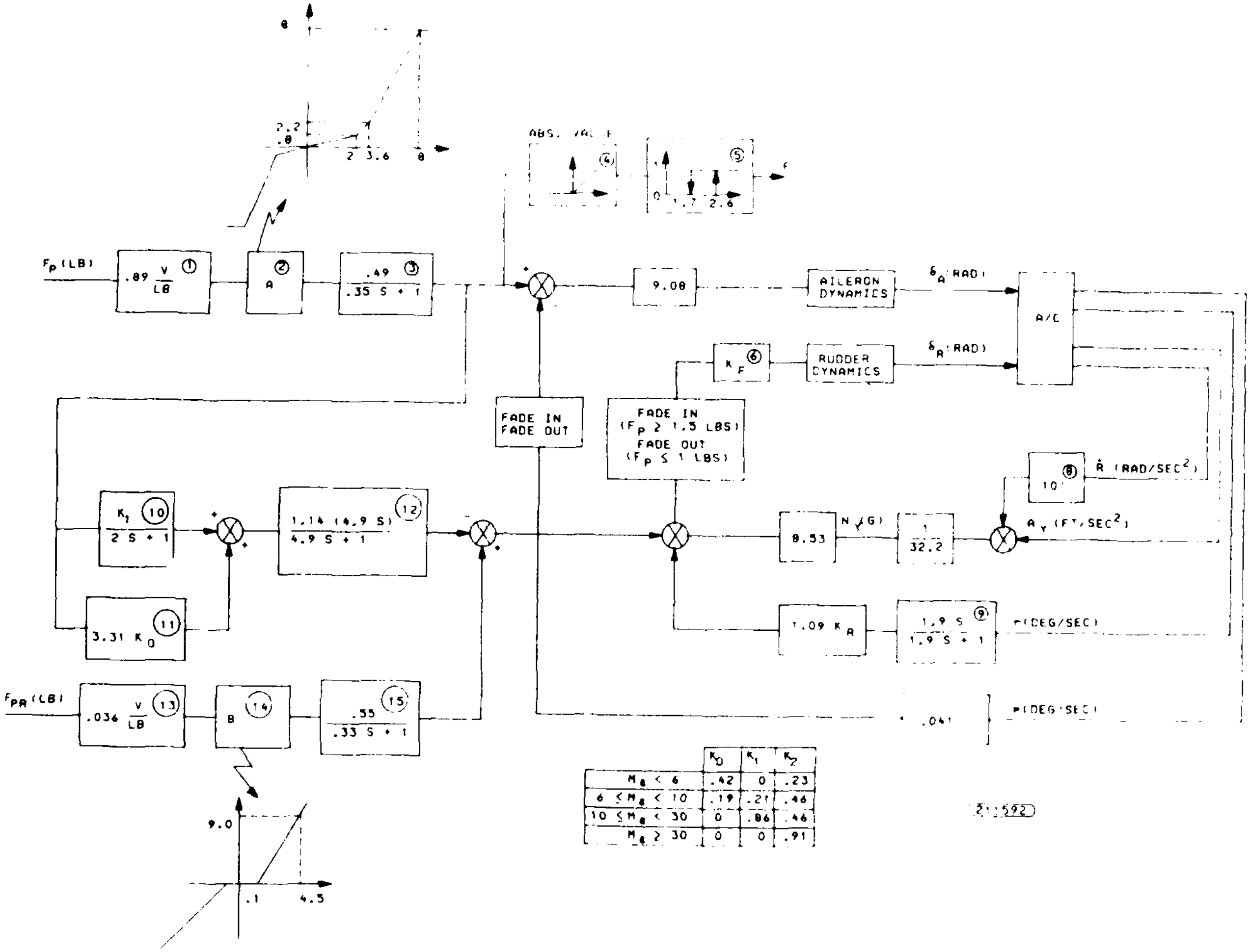
The control system McDonnell Douglas designed to meet these three criteria is shown in block diagram form in Figures B-1 and B-2. These block diagrams represent a simplified version of the control system where only those blocks which have a major effect on the flight control are included. Individual blocks in the block diagram are labeled so that they can be referred to in subsequent discussions.

The pilot input to the longitudinal control system is shaped by Blocks 1, 2, and 3. Block 1 scales the pilot input. Block 2 is a non-linear gain that provides a low sensitivity to pilot inputs near neutral commands while large pilot inputs are not required for large commands. Block 3 is a dynamic prefilter employed to slow down initial response to pilot input. Normal acceleration at the pilot station and pitch rate are the feedback controls. The normal acceleration is passed through Block 9 to filter out the body bending modes. The feedback controls are activated when the force on the side stick exceeds 2.0 lbs and de-activated when less than 1.5 lbs. Blocks 6 and 7 determine the fade in/fade out switching of Block 10. The feedback controls are switched in with a time constant of 0.3 sec and switched out with a time constant of 0.7 sec. K_δ (Block 4) is an adaptive gain which is a function of the stability derivative M_δ. M_δ is commonly referred to as the elevator effectiveness or elevator power. For the 4D IFTC real-time simulation, M_δ is computed from values of $C_{M_{\delta_e}}$ stored in a table where

$$M_\delta = \frac{\frac{1}{2}\rho V_T^2 S\bar{c}}{I_{yy}} C_{M_{\delta_e}}$$



PITCH CHANNEL - SURVIVABLE FLIGHT CONTROL SYSTEM
FIGURE B-1



	K_0	K_1	K_2
$M_\phi < 6$	.42	0	.23
$6 \leq M_\phi < 10$	.19	.21	.46
$10 \leq M_\phi < 30$	0	.86	.46
$M_\phi \geq 30$	0	0	.91

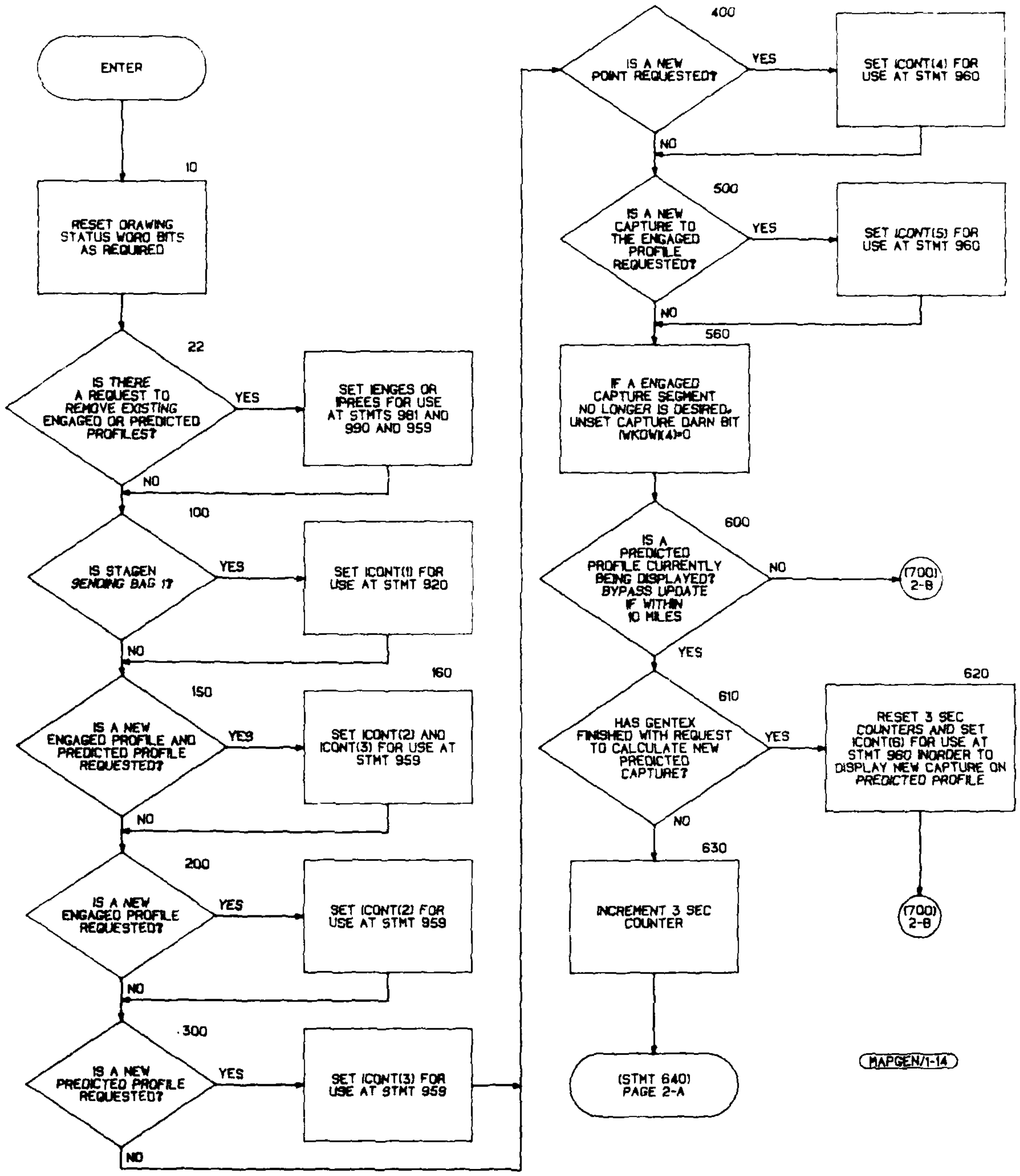
ROLL CHANNEL - SURVIVABLE FLIGHT CONTROL SYSTEM
FIGURE B-2

$K\delta$ then provides a gain scheduling that varies as a function of flight condition. Block 5 is additional compensation used to meet the C* criteria. The remaining blocks are self-explanatory.

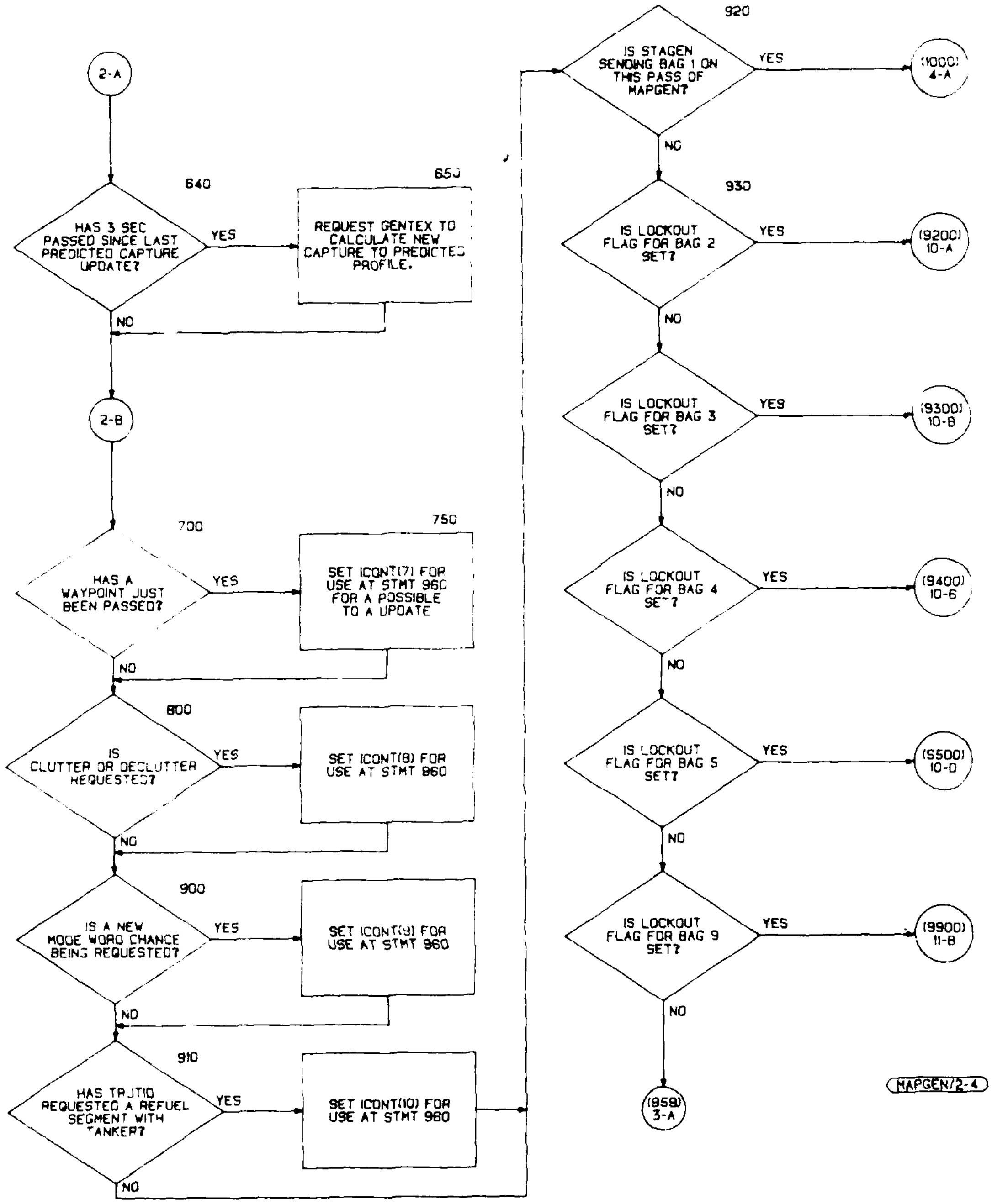
Pilot inputs to the lateral-directional control system are shaped in much the same manner as the longitudinal control system with one exception. Blocks 10, 11, and 12 are crossfeed inputs to the directional axis from the side stick. The lateral control system feeds back roll rate, providing additional damping for the rolling mode. The directional control system employs lateral acceleration at the pilot's station and yaw rate as feedbacks. These feedbacks augment dutch roll damping and provide turn coordination. The yaw rate is washed out by Block 9 in order to prevent rudder deflection during steady-state turns. This would result in an uncoordinated maneuver. The feedback control switching is performed in the same manner as the longitudinal control system. The gains K_0, K_1 and K_R are functions of $M\delta$ and provide gain scheduling in order to meet the D* and roll rate criteria throughout the flight regime. K_f (Block 6) is an attenuation factor due to rudder flexibility.

APPENDIX C

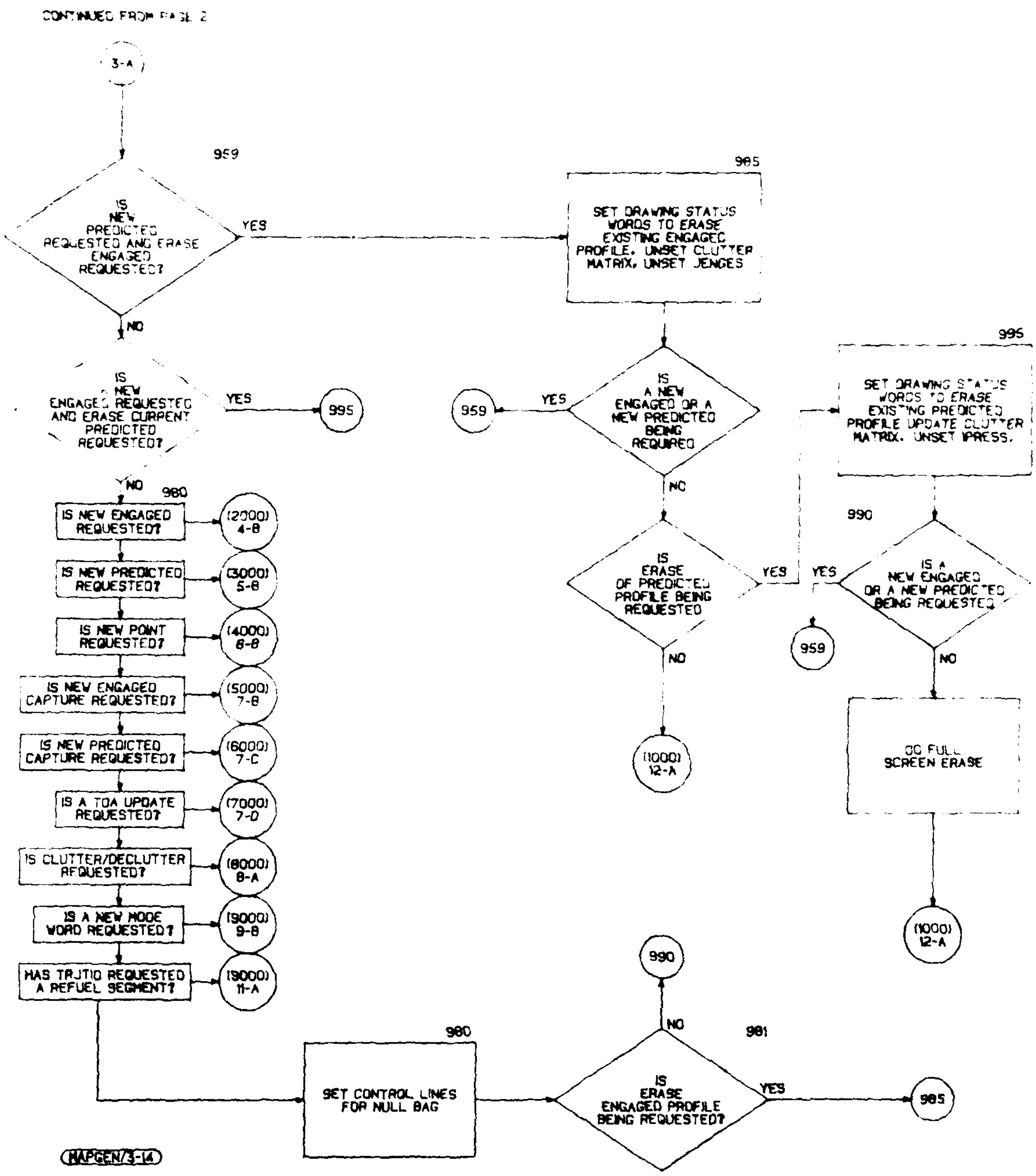
PROGRAM FLOW CHARTS



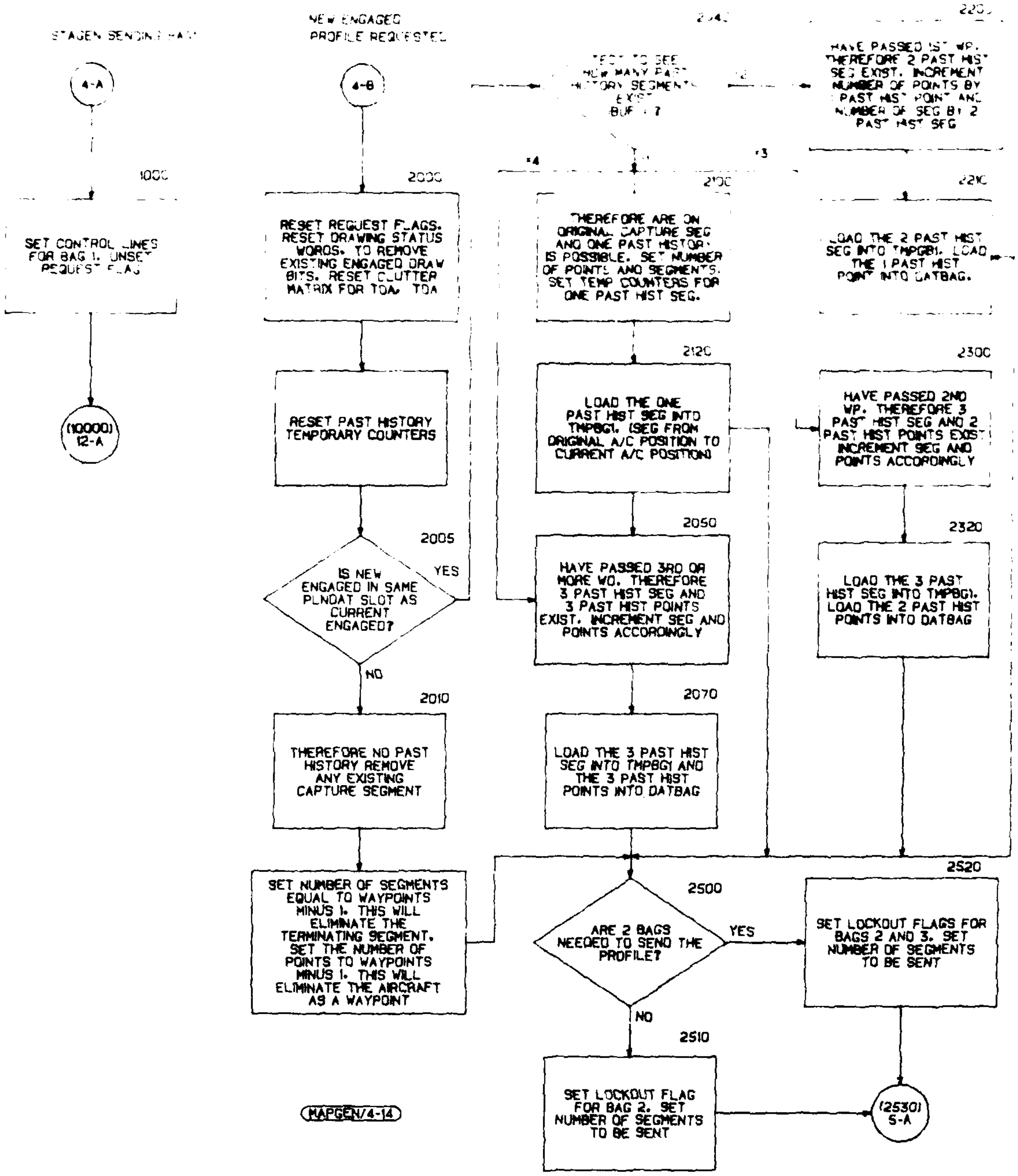
SUBROUTINE MAPGEN (TSD PROCESSING)
FIGURE C-1 (1 of 14)



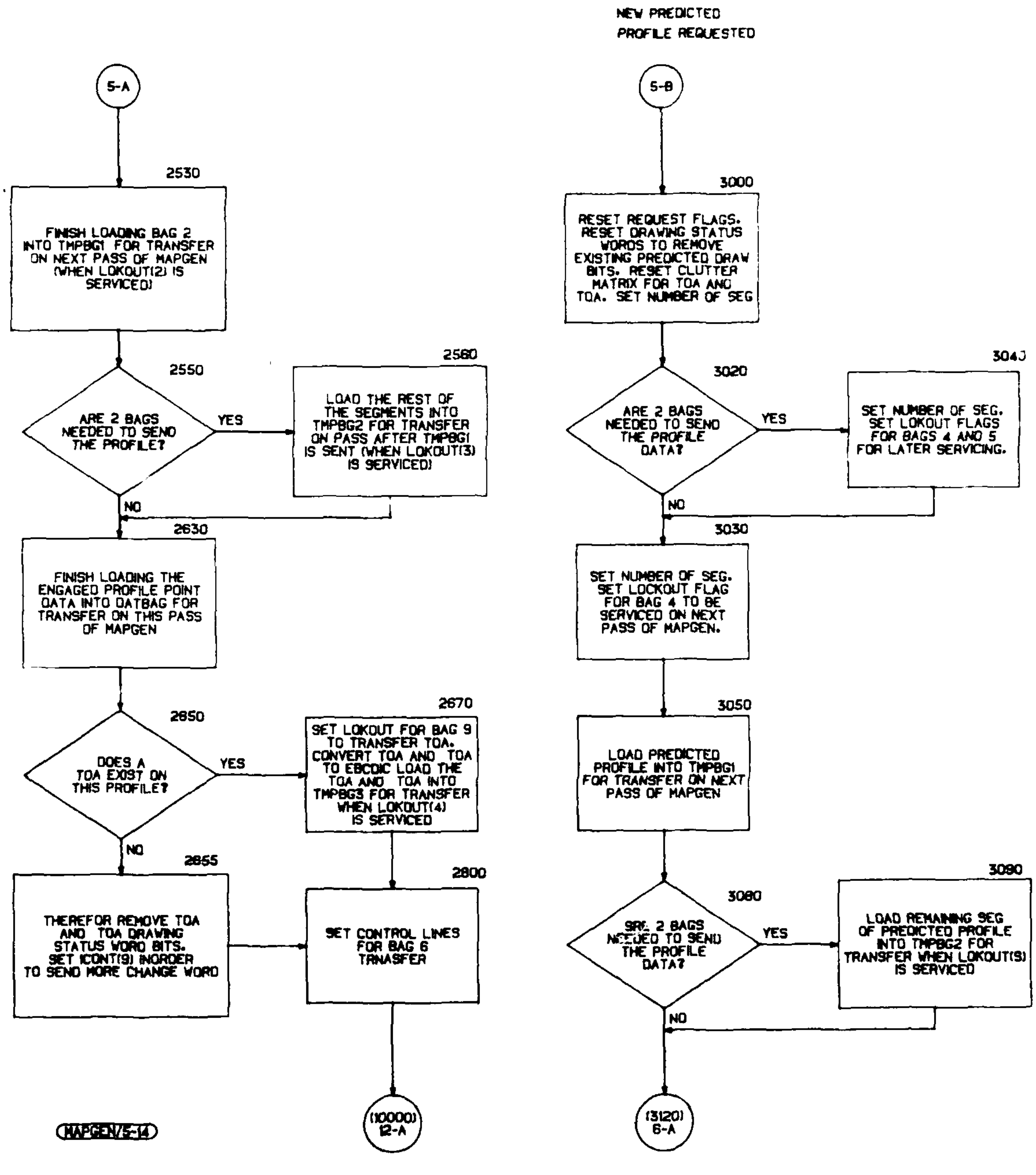
SUBROUTINE MAPGEN (TSD PROCESSING)
FIGURE C-1 (2 of 14)



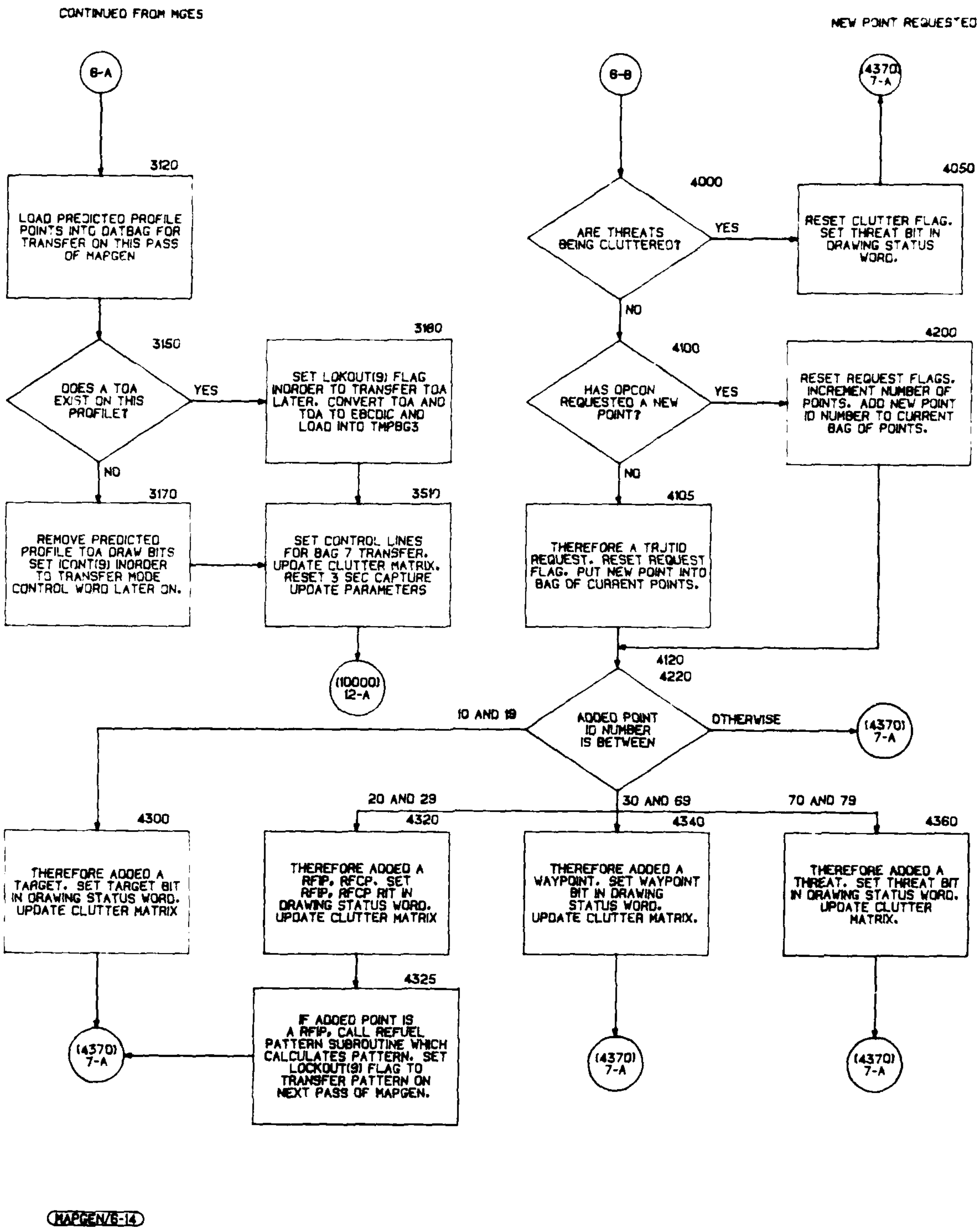
SUBROUTINE MAPGEN (TSD PROCESSING)
FIGURE C-1 (3 of 14)



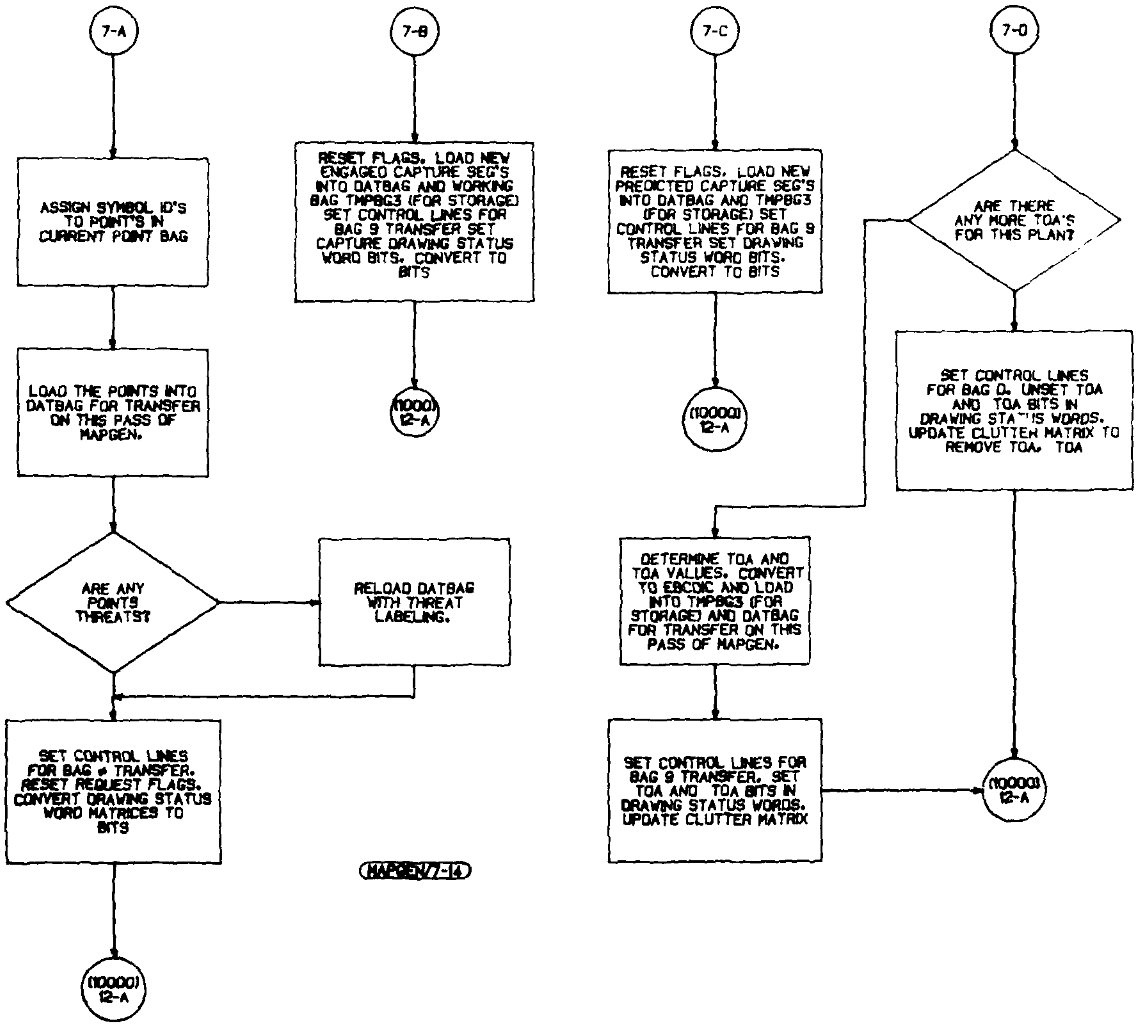
SUBROUTINE MAPGEN (TSD PROCESSING)
FIGURE C-1 (4 of 14)



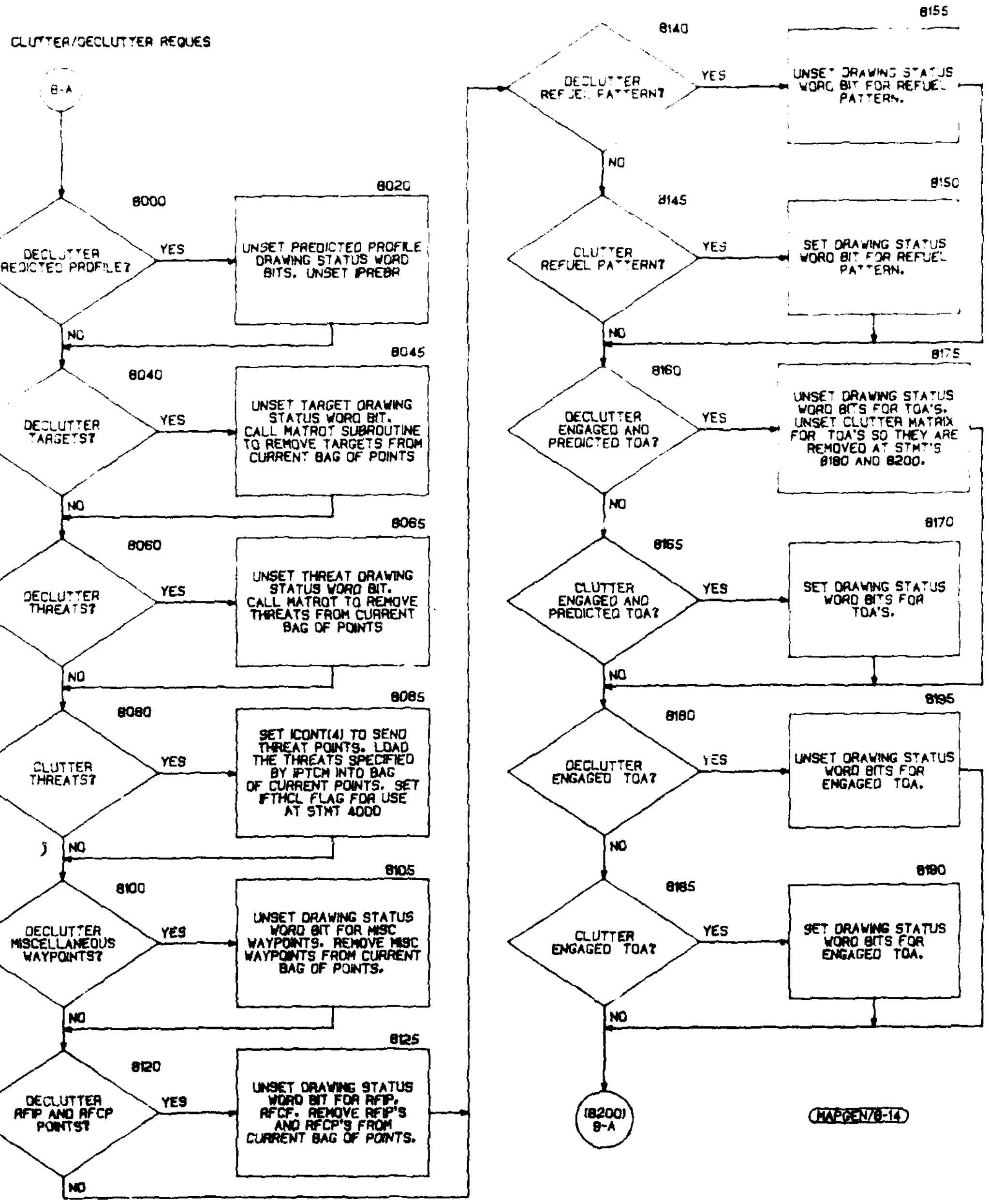
SUBROUTINE MAPGEN (TSD PROCESSING)
FIGURE C-1 (5 of 14)



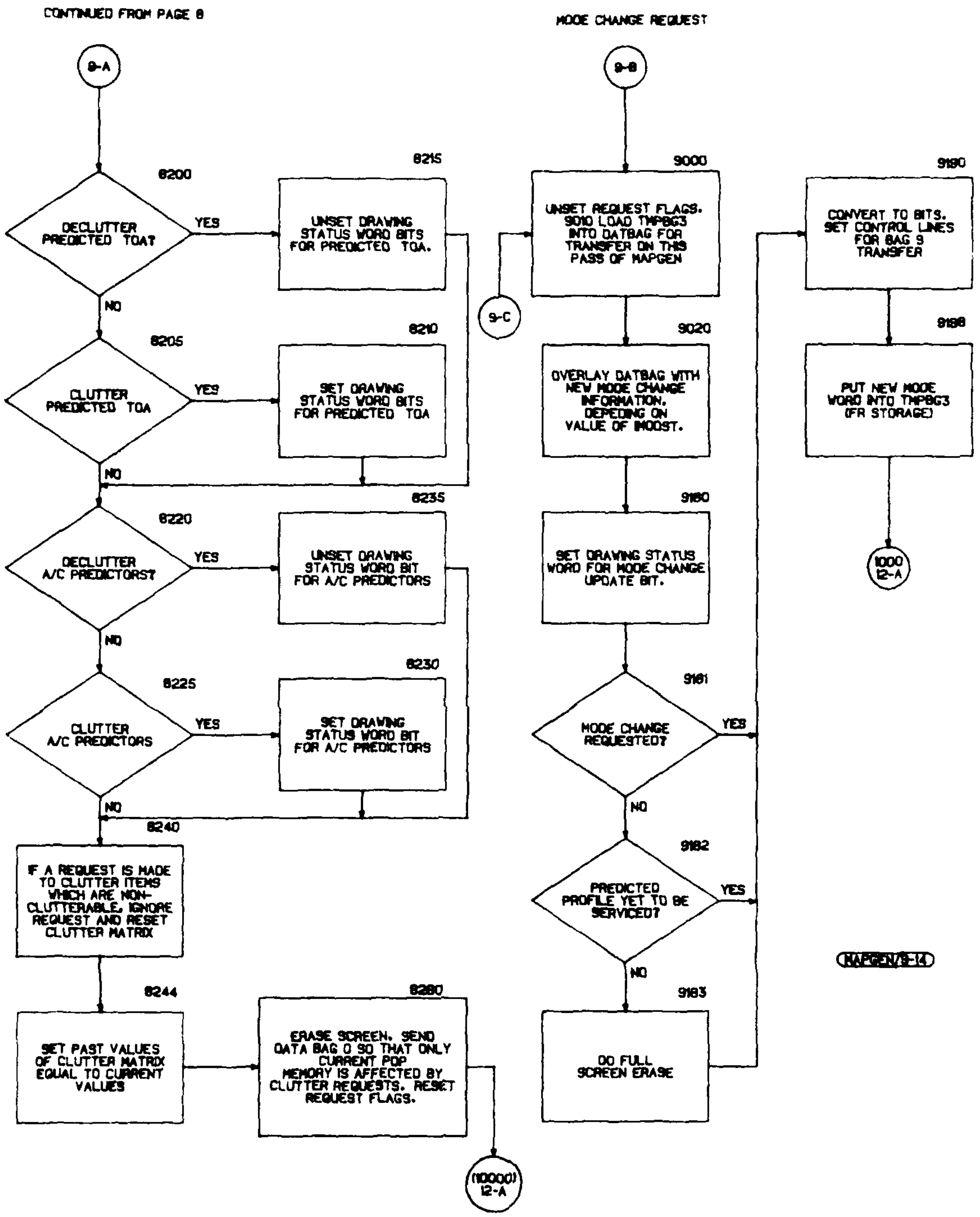
SUBROUTINE MAPGEN (TSD PROCESSING)
FIGURE C-1 (6 of 14)



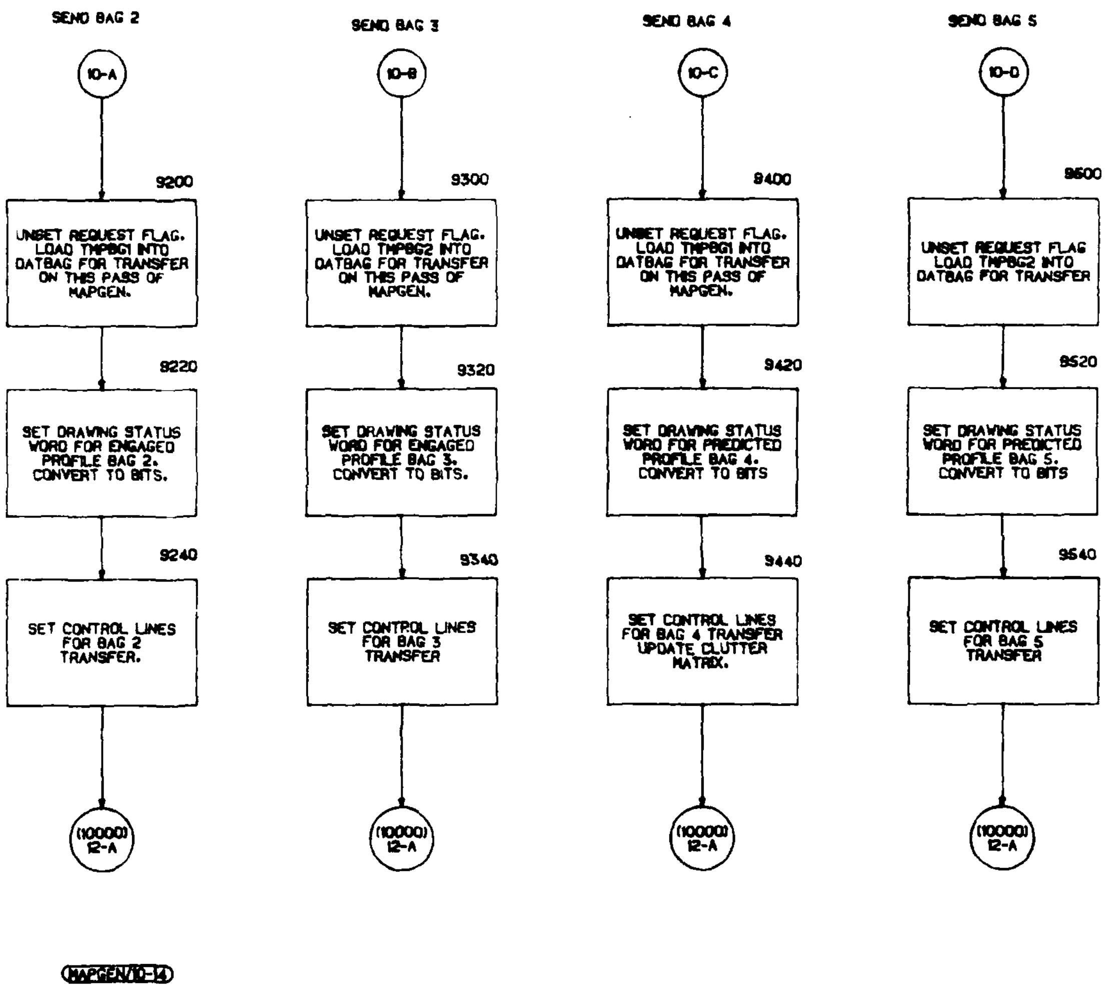
SUBROUTINE MAPGEN (TSD PROCESSING)
FIGURE C-1 (7 of 14)



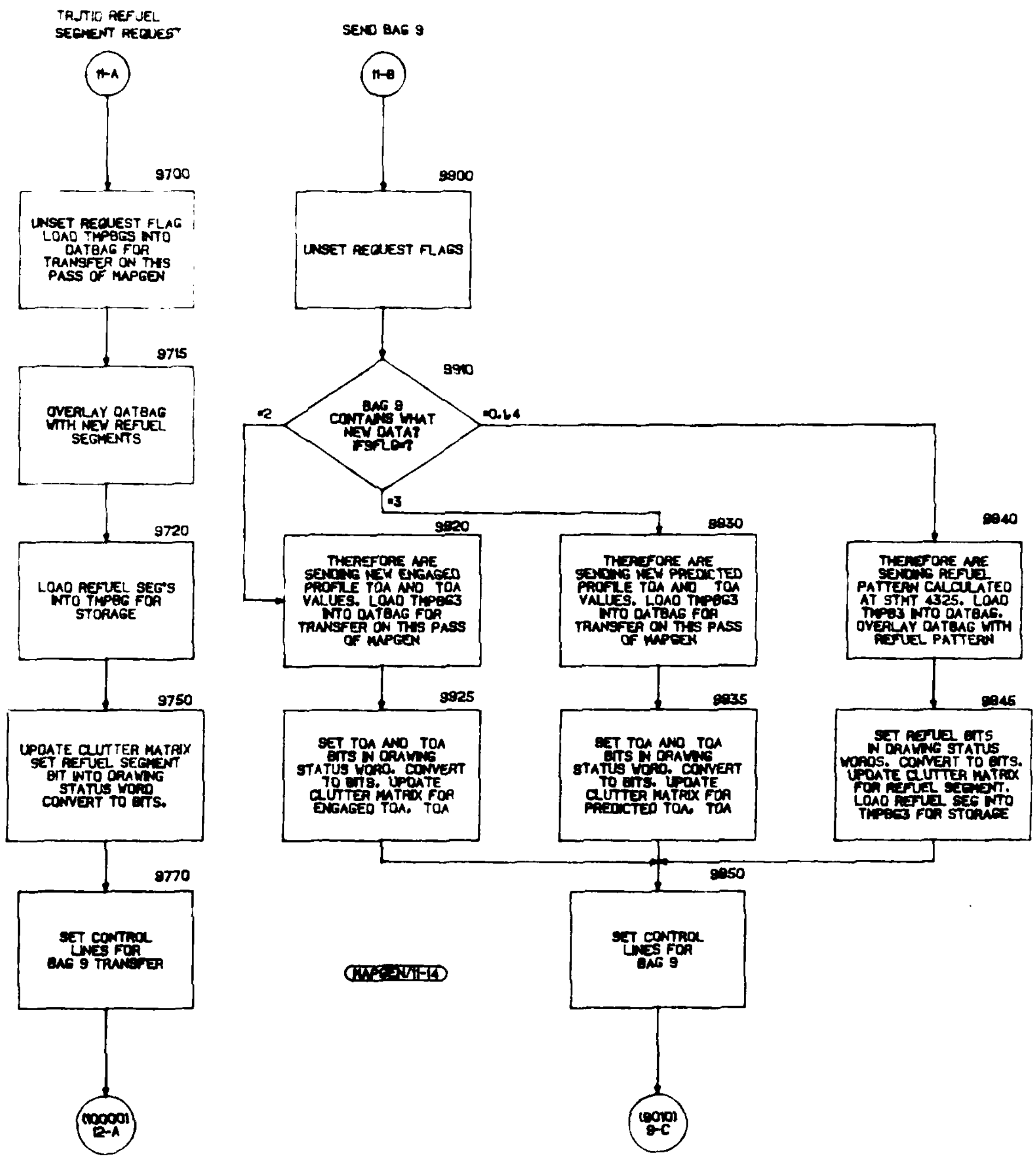
SUBROUTINE MAPGEN (TSD PROCESSING)
FIGURE C-1 (8 of 14)



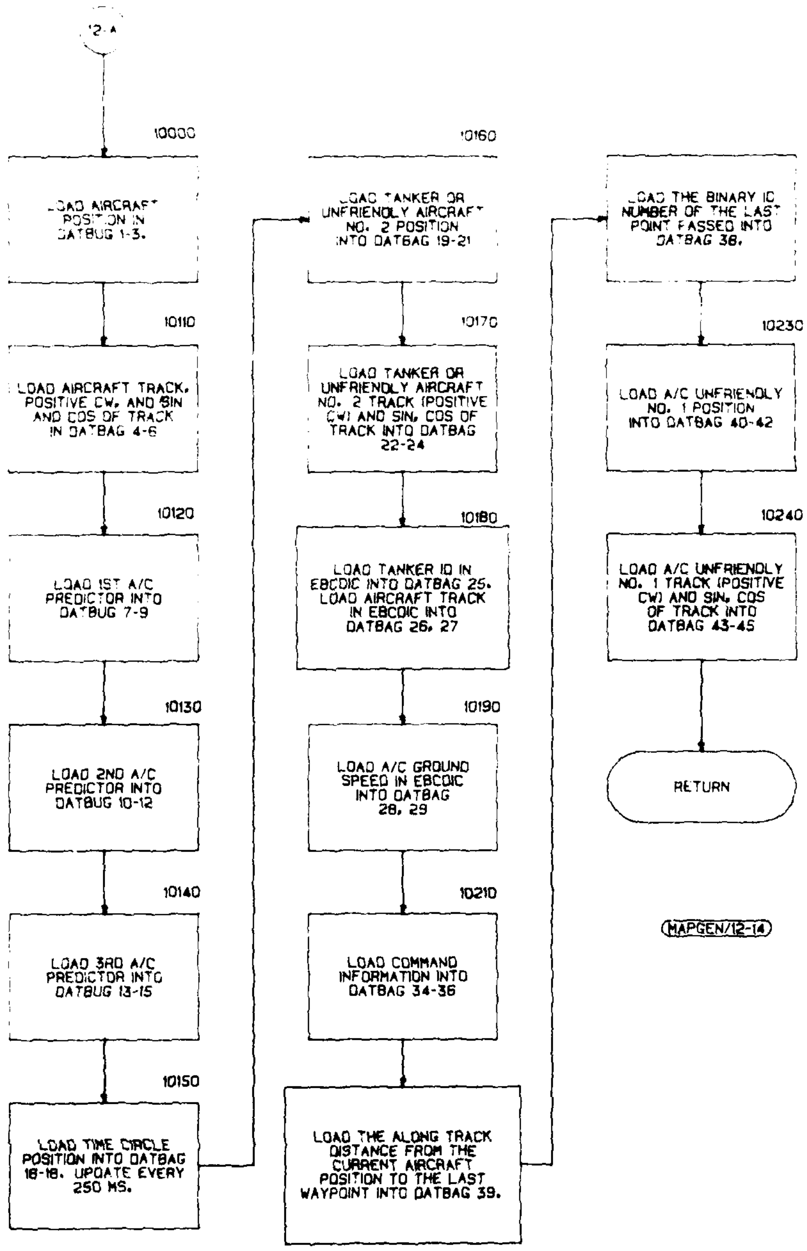
SUBROUTINE MAPGEN (TSD PROCESSING)
FIGURE C-1 (9 of 14)



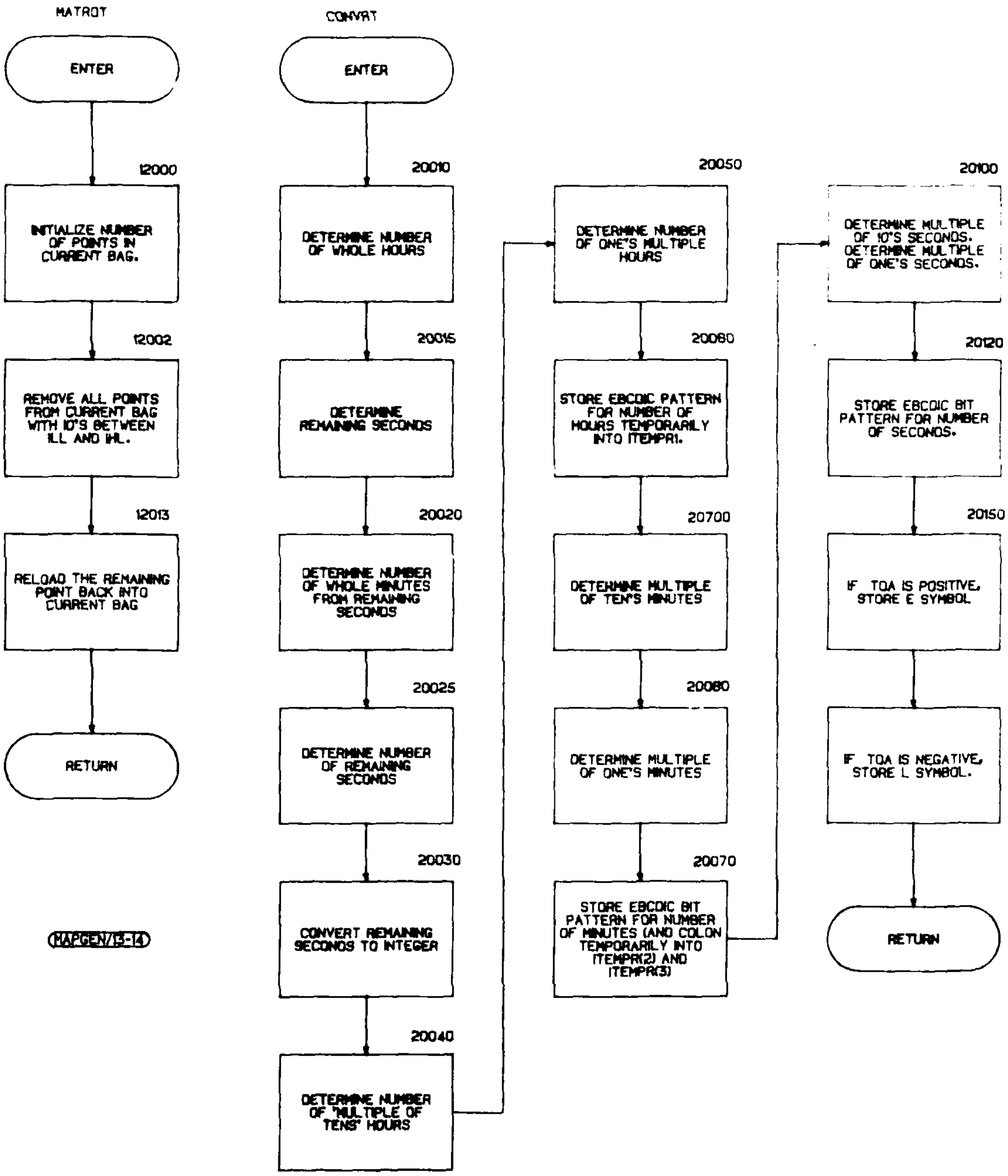
SUBROUTINE MAPGEN (TSD PROCESSING)
FIGURE C-1 (10 of 14)



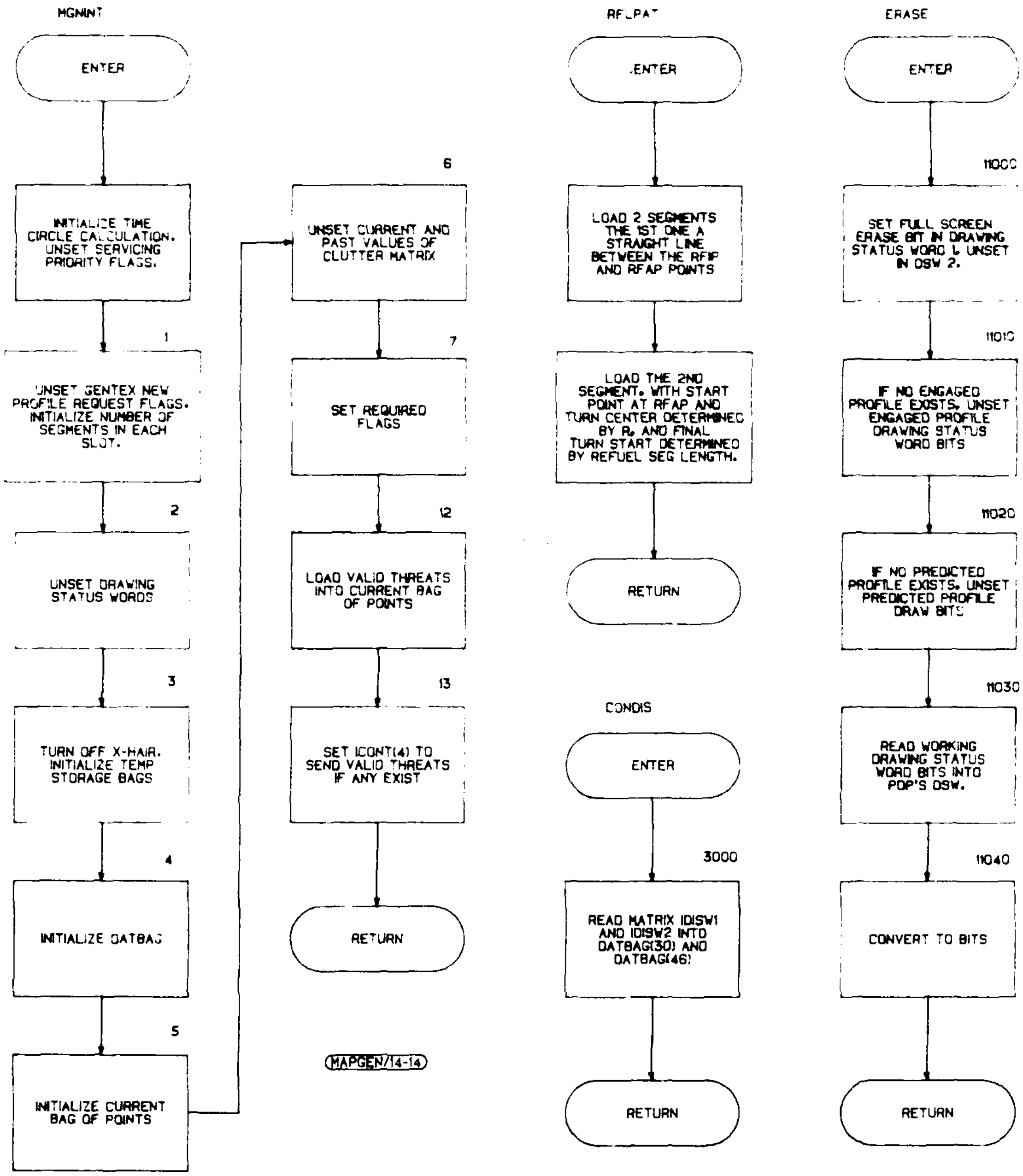
SUBROUTINE MAPGEN (TSD PROCESSING)
FIGURE C-1 (11 of 14)



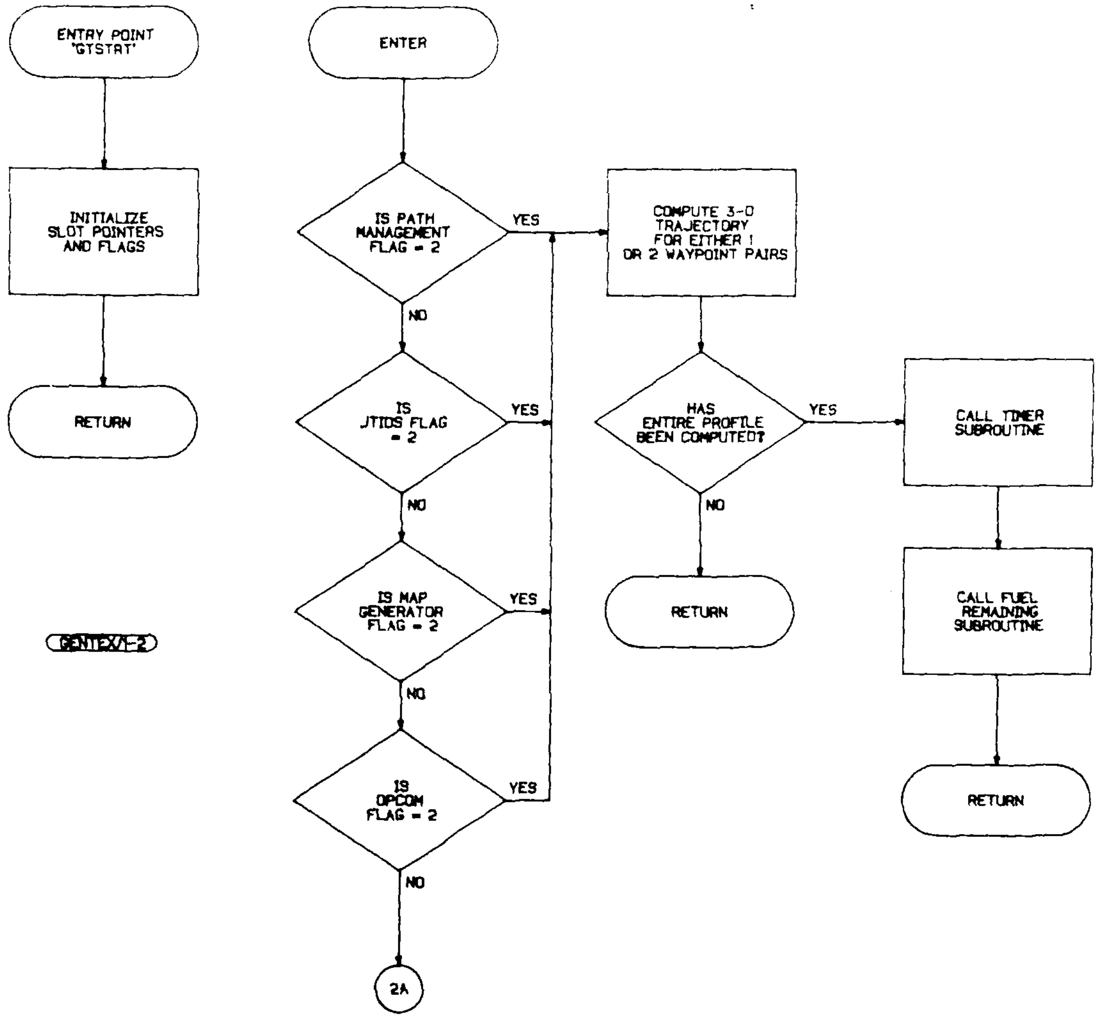
SUBROUTINE MAPGEN (TSD PROCESSING)
FIGURE C-1 (12 of 14)



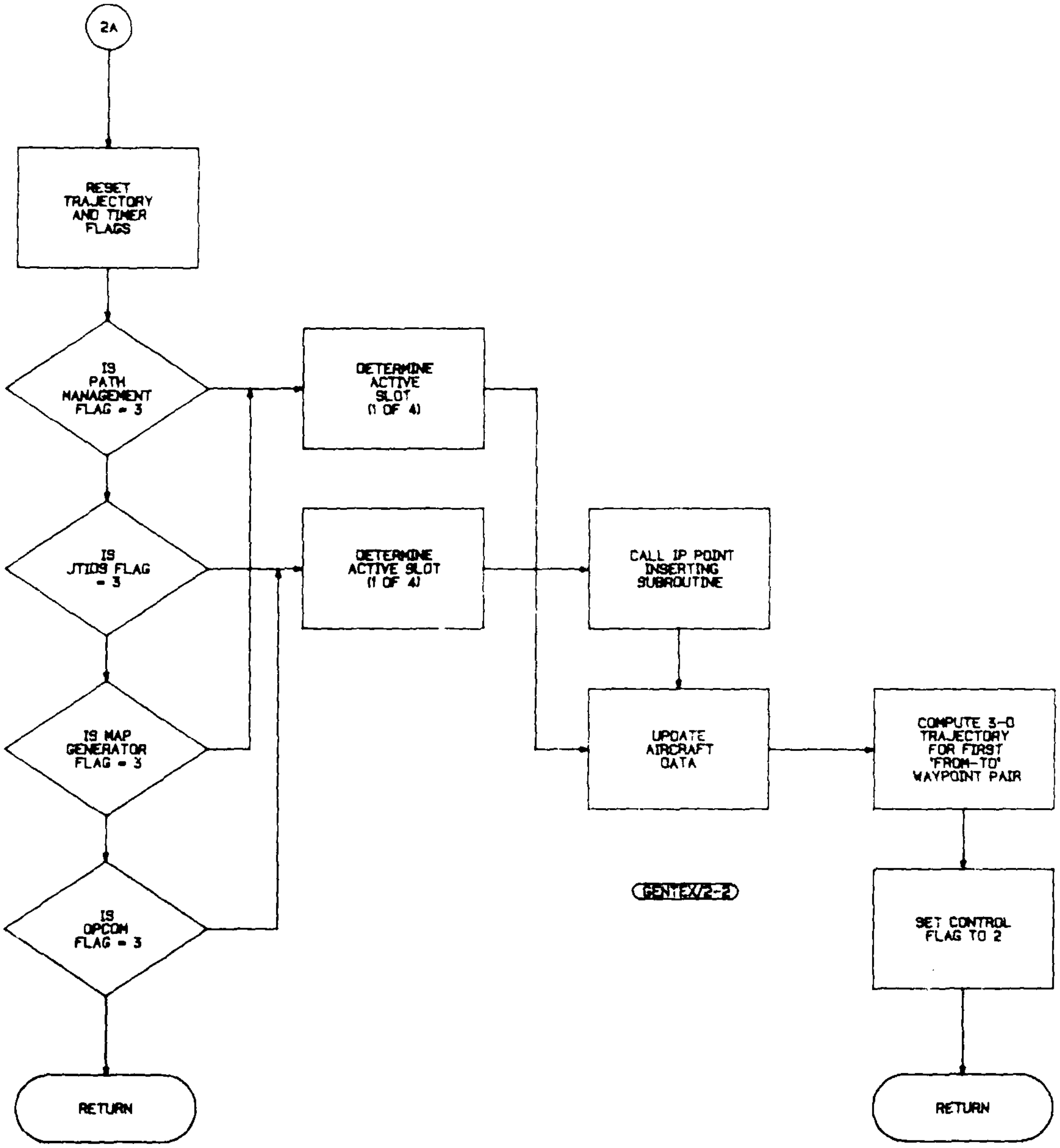
SUBROUTINE MAPGEN (TSD PROCESSING)
FIGURE C-1 (13 of 14)



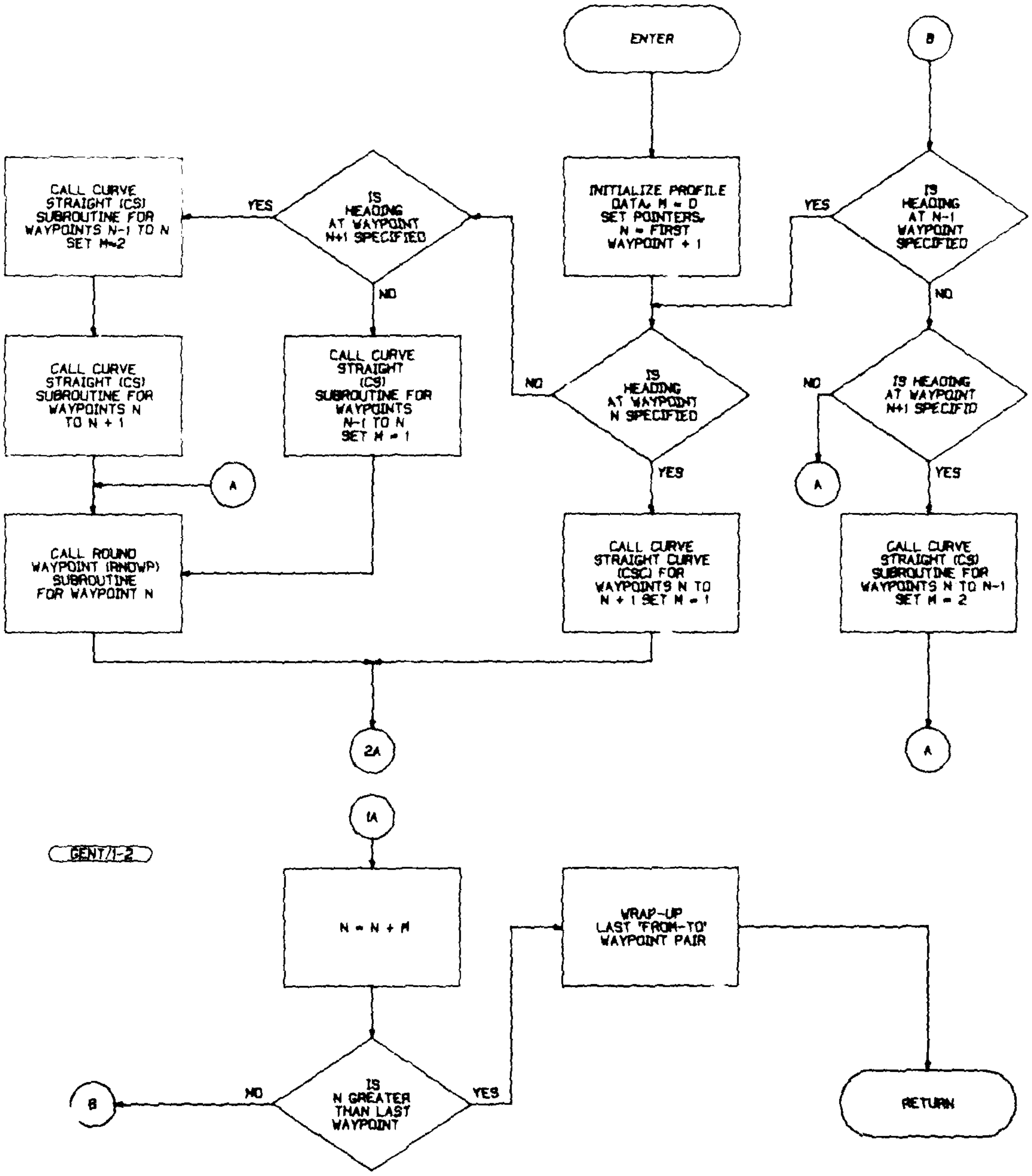
SUBROUTINE MAPGEN (TSD PROCESSING)
FIGURE C-1 (14 of 14)



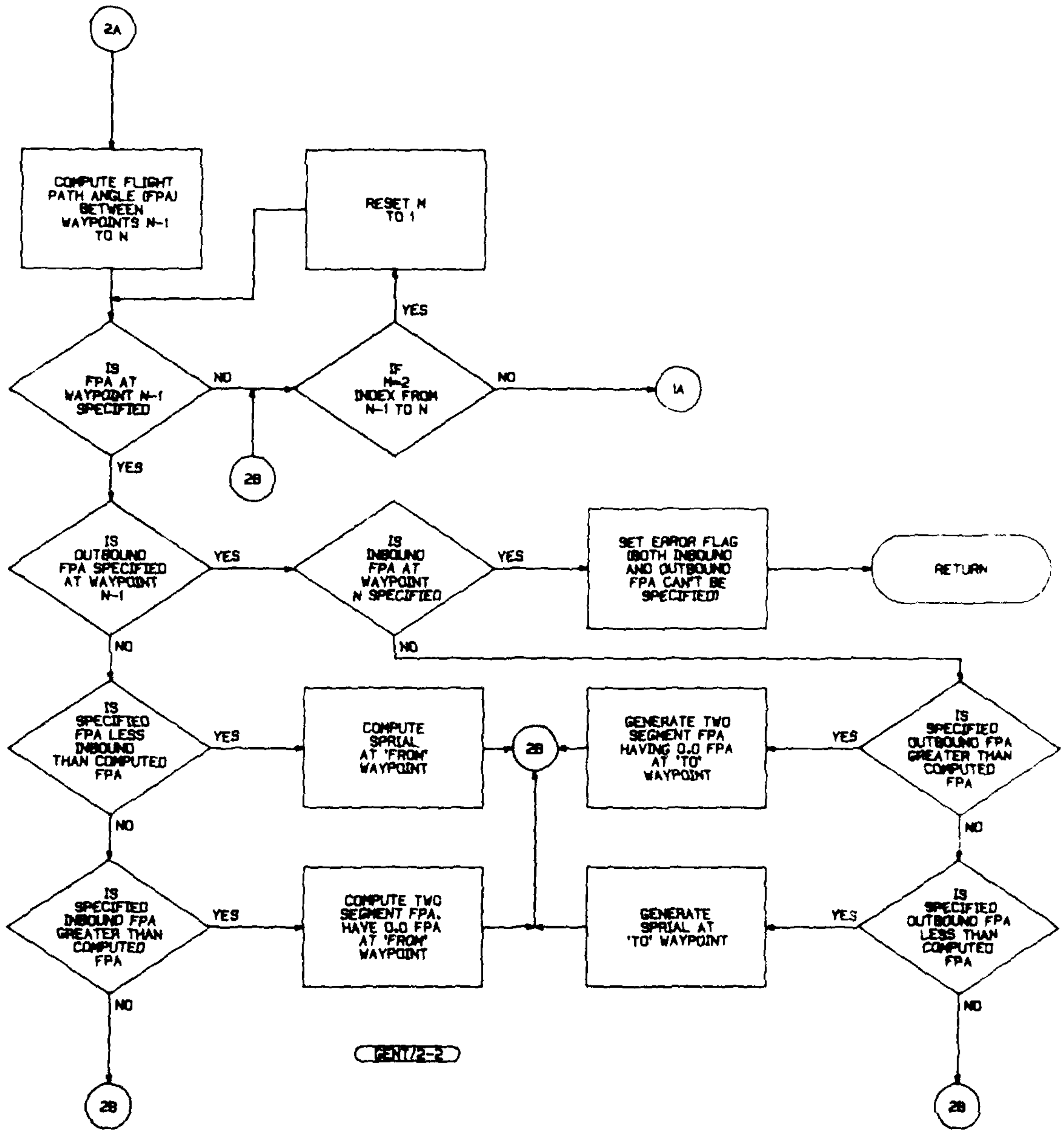
SUBROUTINE GENTEX (TRAJECTORY EXECUTIVE)
FIGURE C-2 (1 of 2)



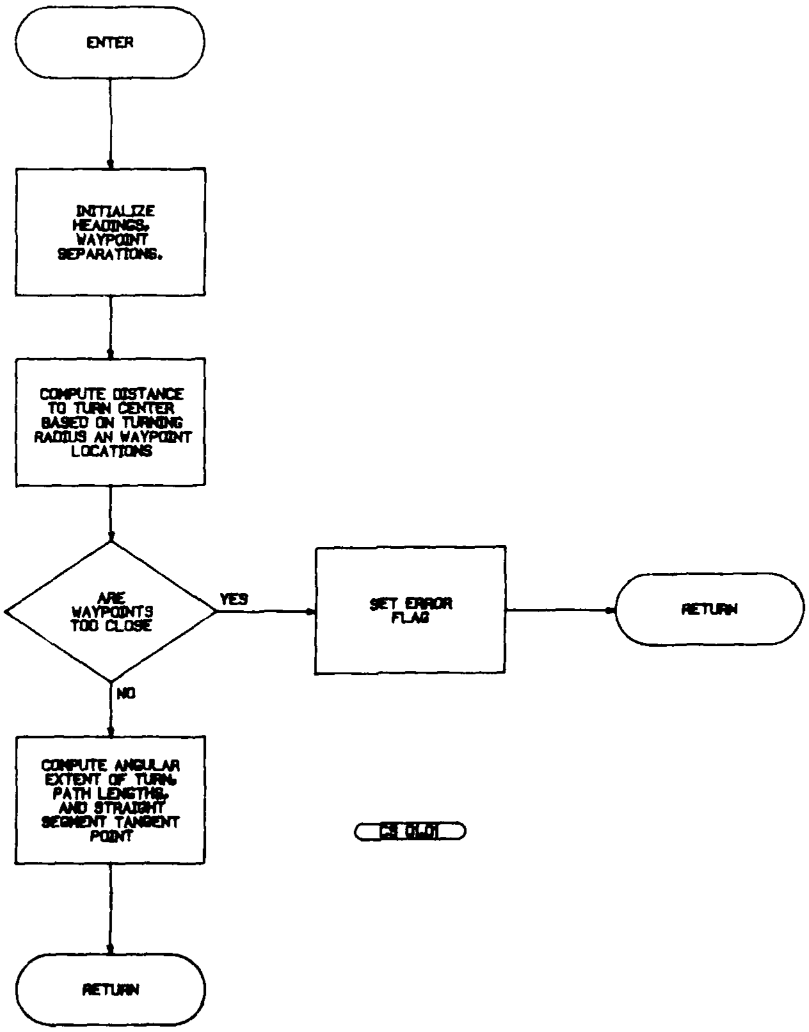
SUBROUTINE GENTEX (TRAJECTORY EXECUTIVE)
FIGURE C-2 (2 of 2)



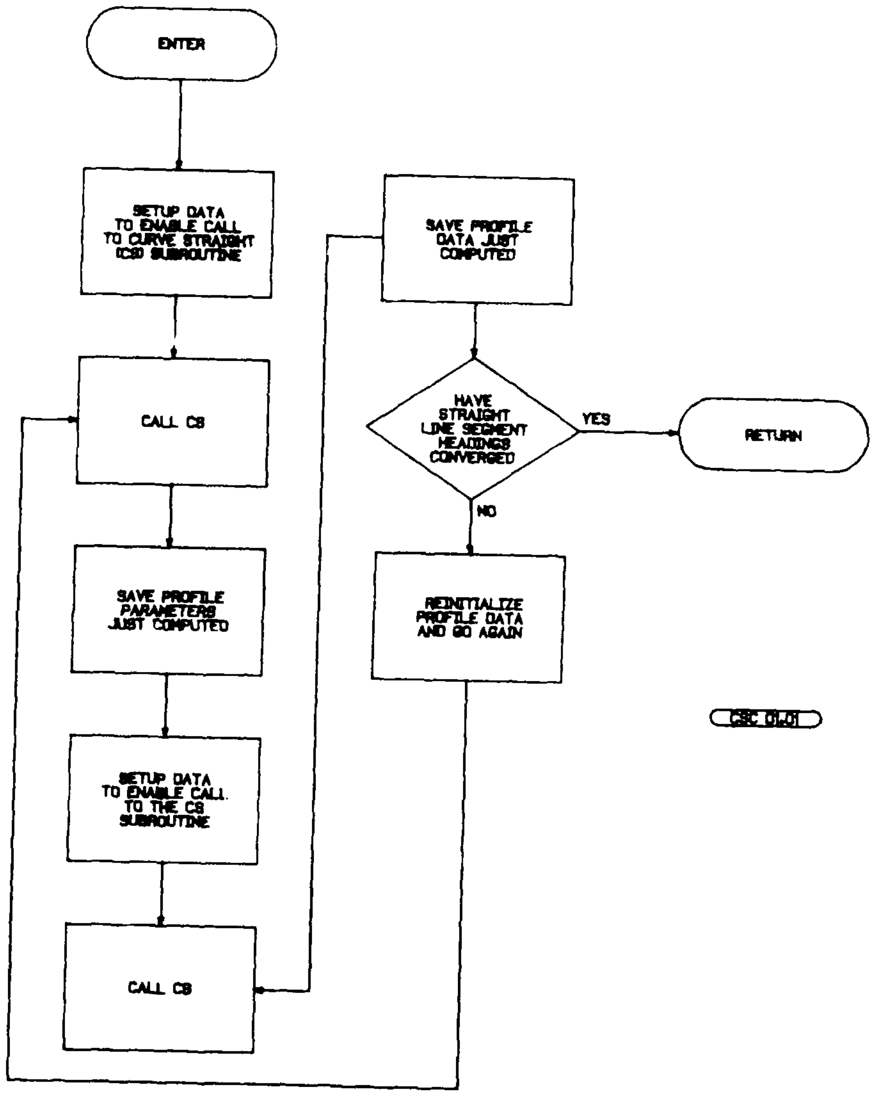
SUBROUTINE GENT (TRAJECTORY GENERATOR)
FIGURE C-3 (1 of 2)



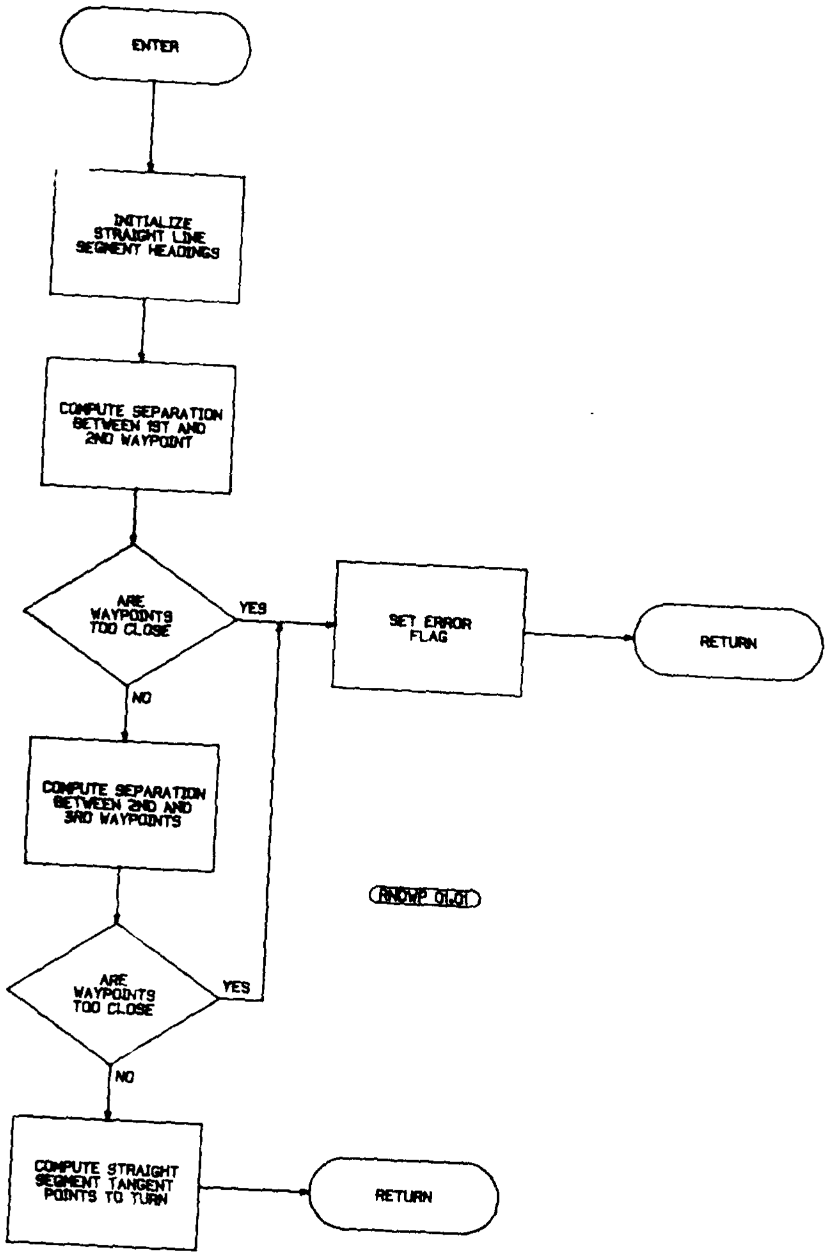
SUBROUTINE GENT (TRAJECTORY GENERATOR)
FIGURE C-3 (2 of 2)



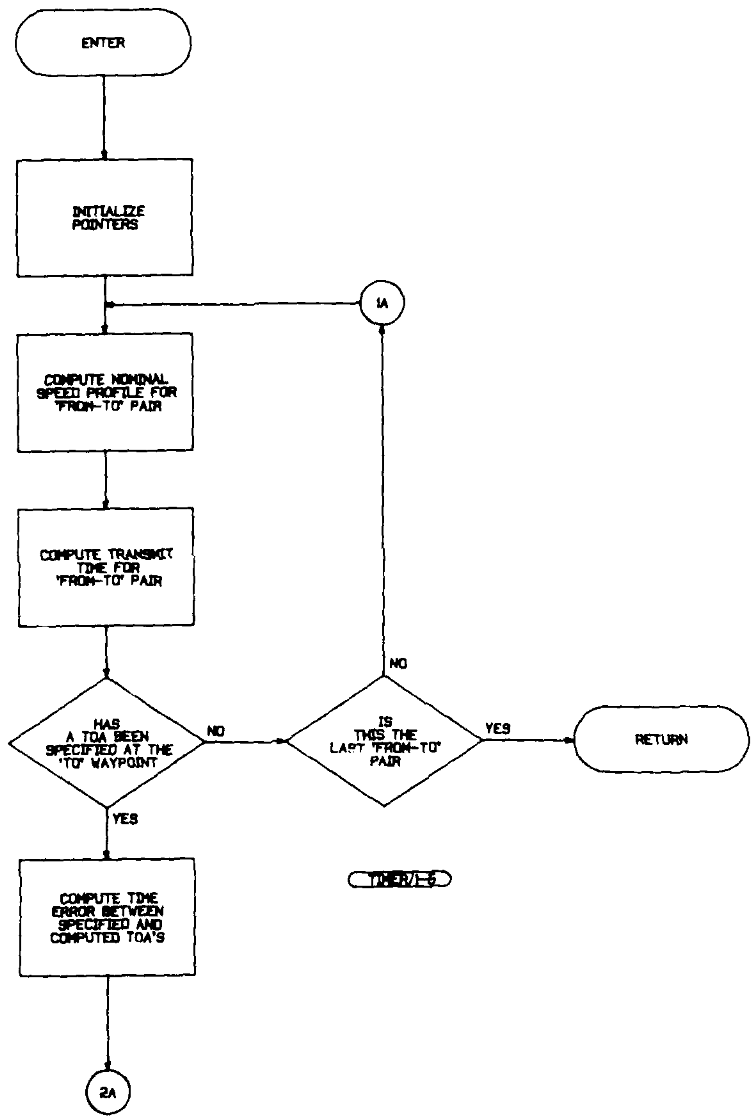
SUBROUTINE CS (CURVED-STRAIGHT)
FIGURE C-4



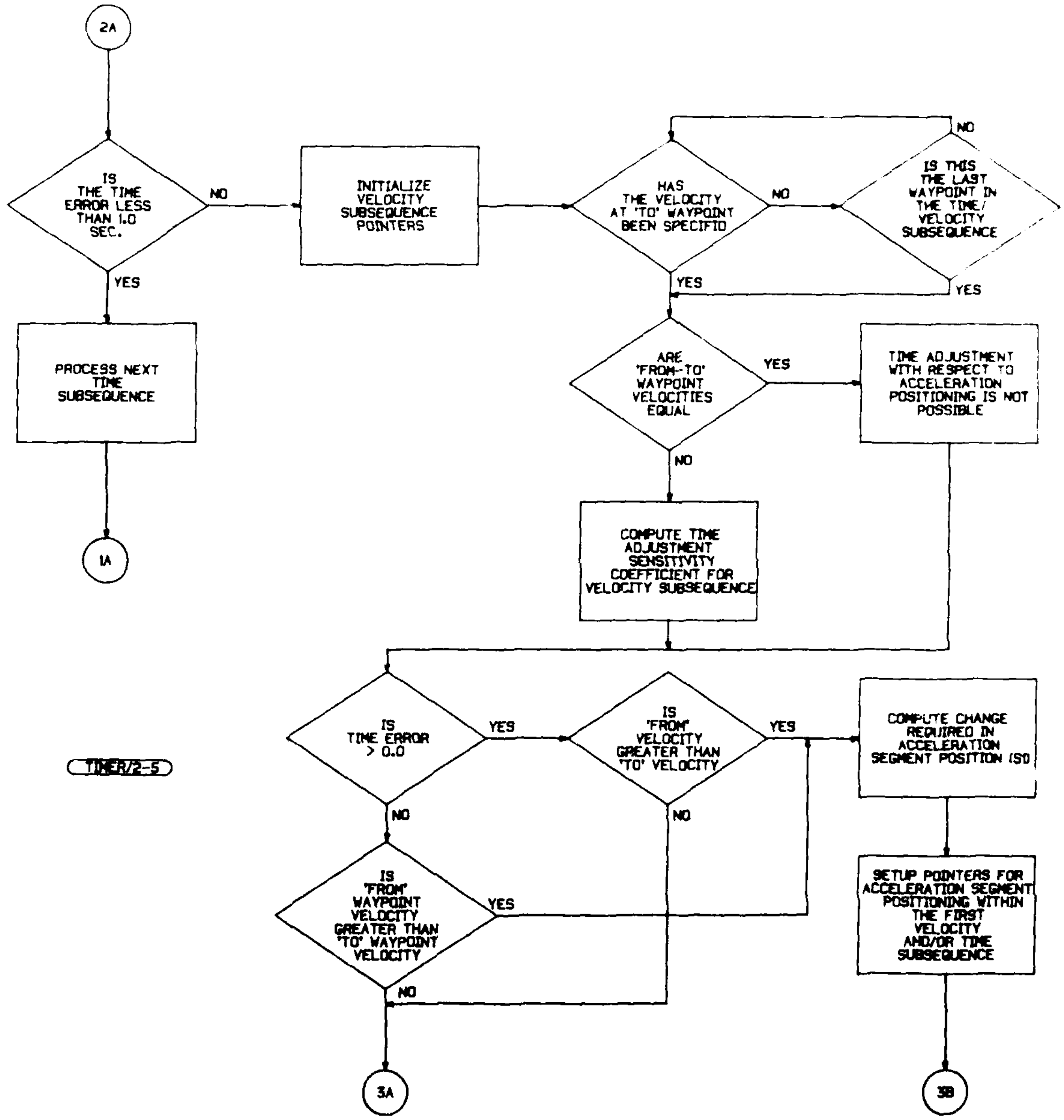
SUBROUTINE CSC (CURVED-STRAIGHT-CURVED)
FIGURE C-5



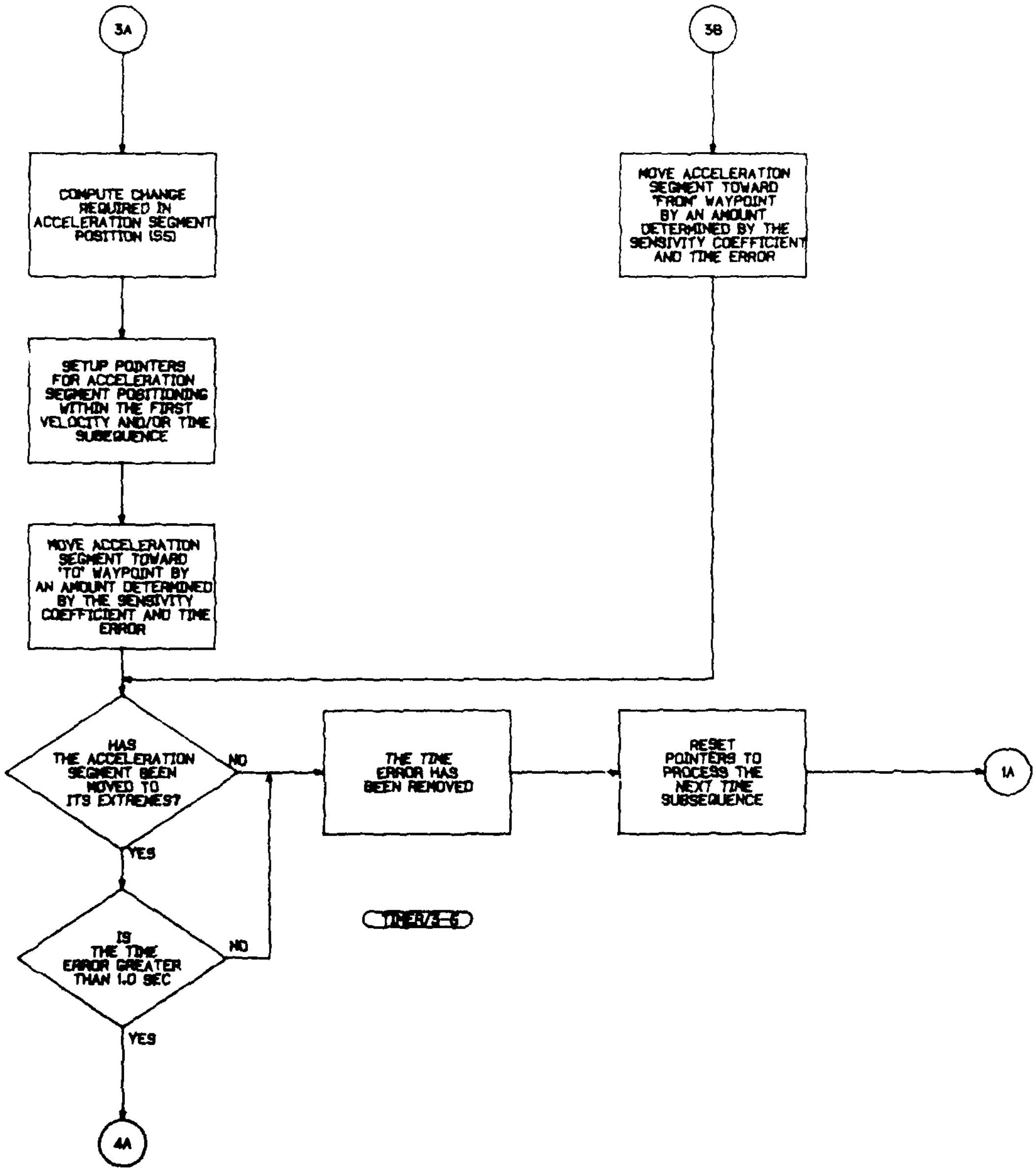
SUBROUTINE RNDWP (ROUND WAYPOINT)
FIGURE C-6



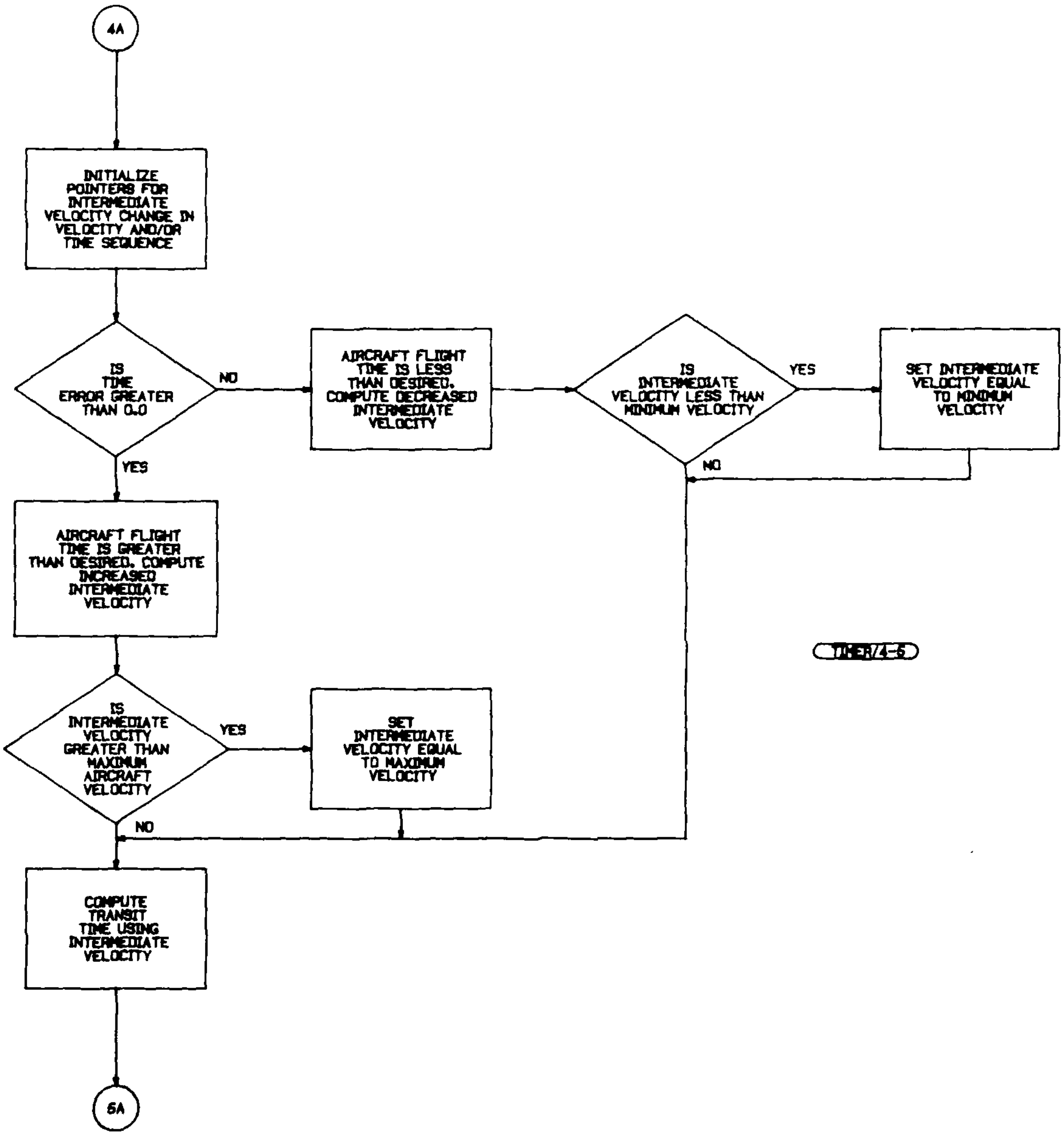
SUBROUTINE TIMER
FIGURE C-7 (1 of 5)



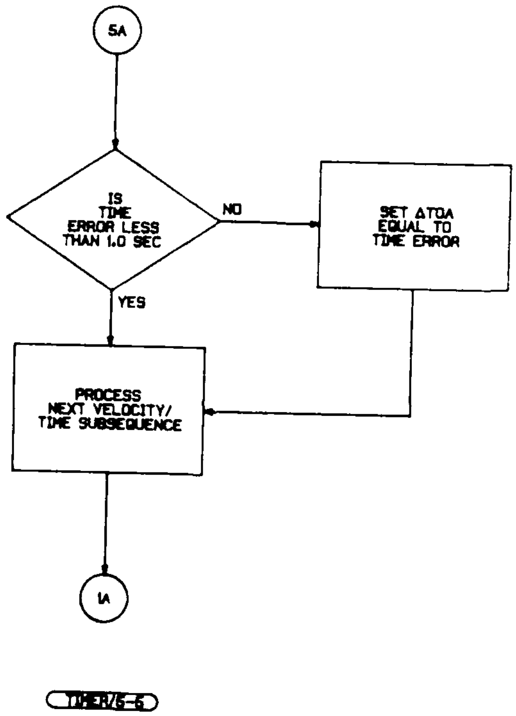
SUBROUTINE TIMER
FIGURE C-7 (2 of 5)



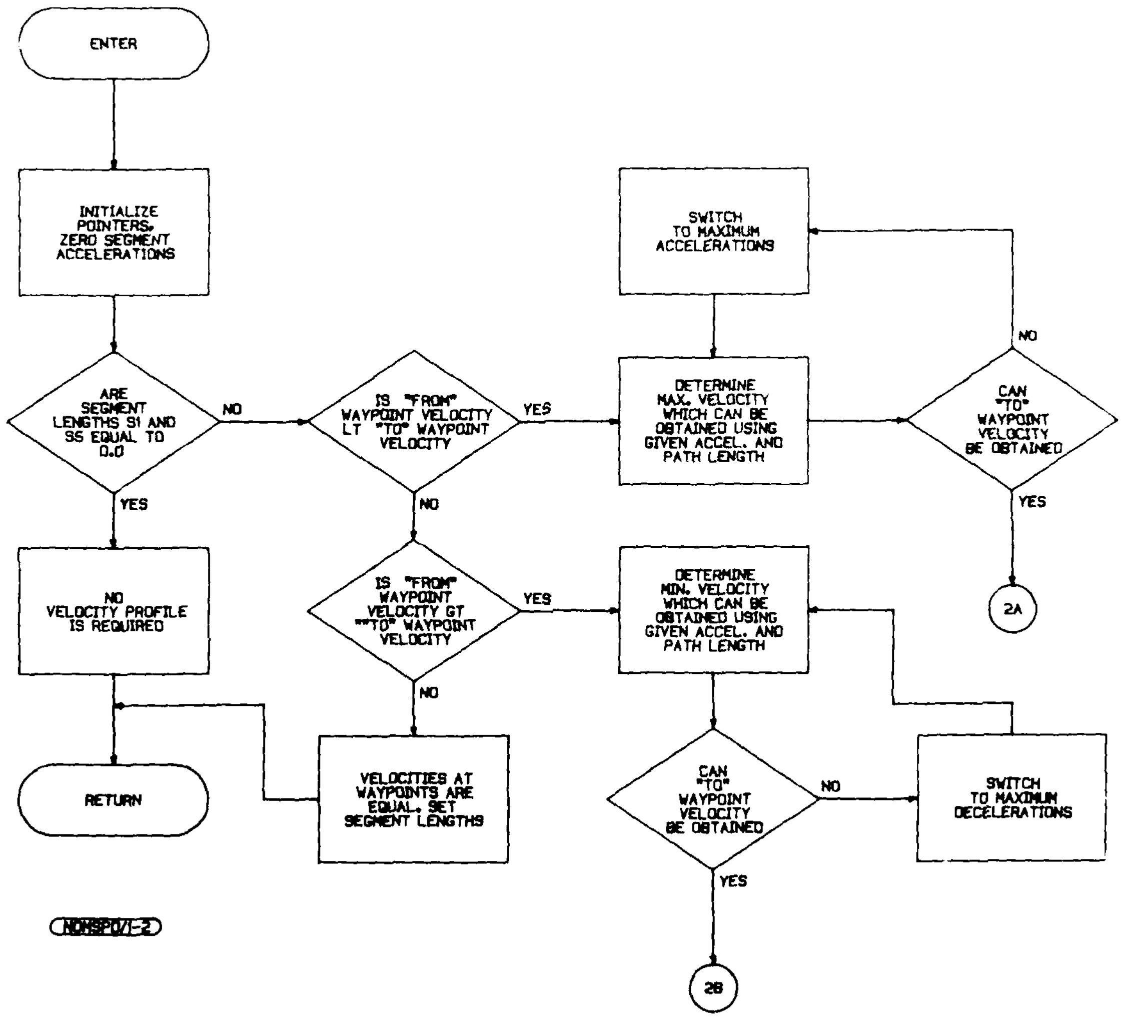
SUBROUTINE TIMER
FIGURE C-7 (3 of 5)



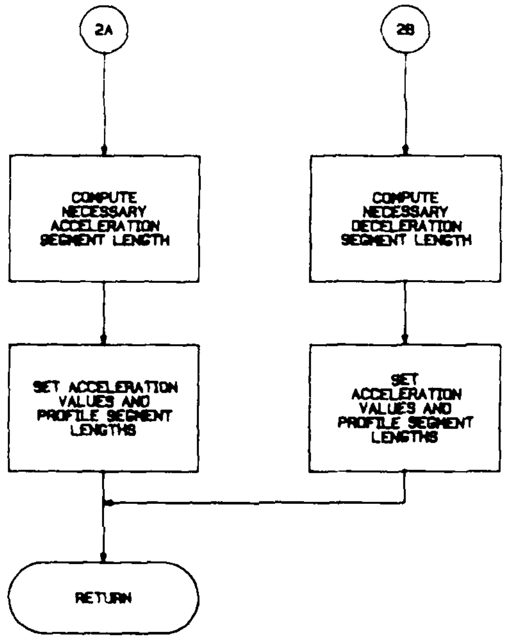
SUBROUTINE TIMER
FIGURE C-7 (4 of 5)



SUBROUTINE TIMER
FIGURE C-7 (5 of 5)

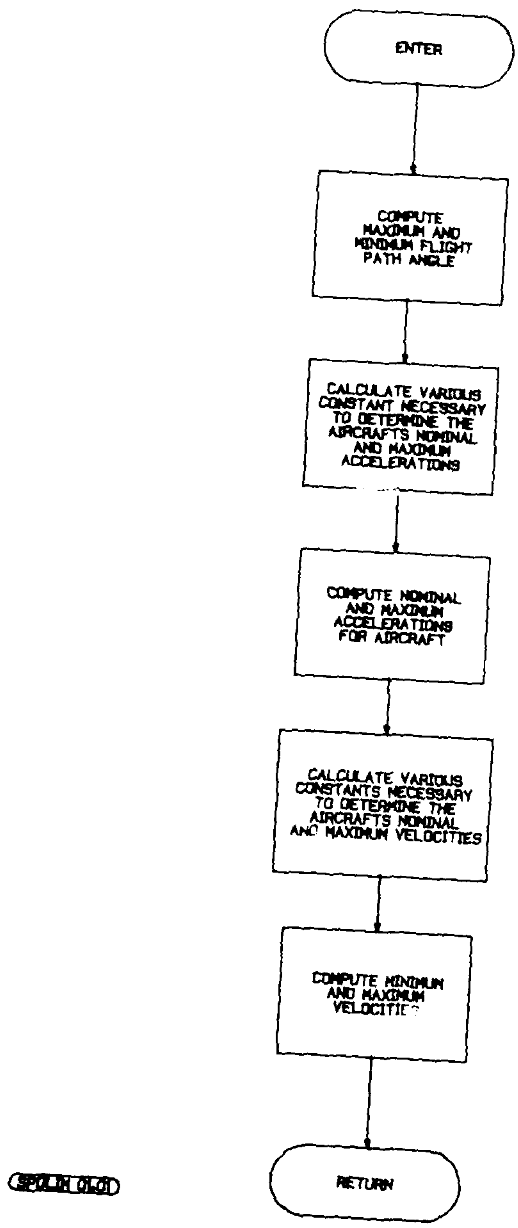


SUBROUTINE NOMSPD (NOMINAL SPEED)
FIGURE C-8 (1 of 2)

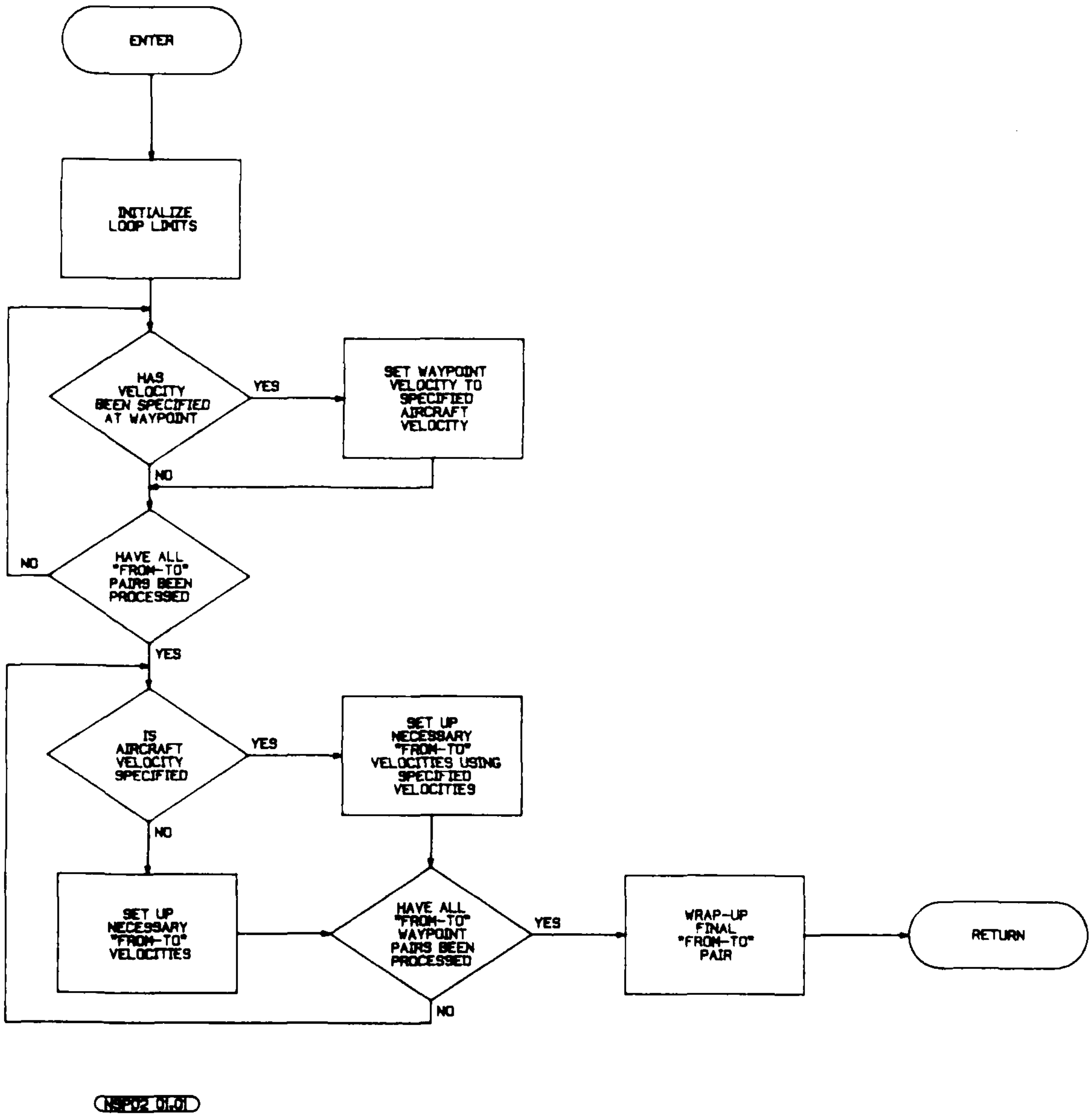


NOMSPD/2-2

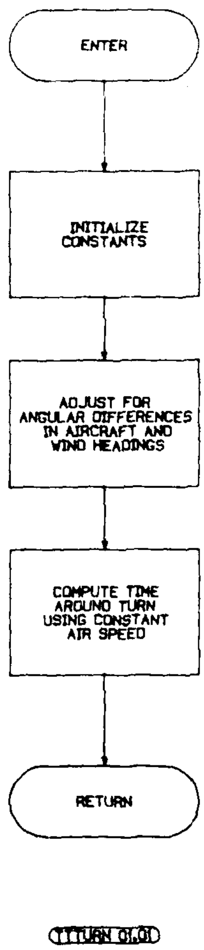
SUBROUTINE NOMSPD (NOMINAL SPEED)
FIGURE C-8 (2 of 2)



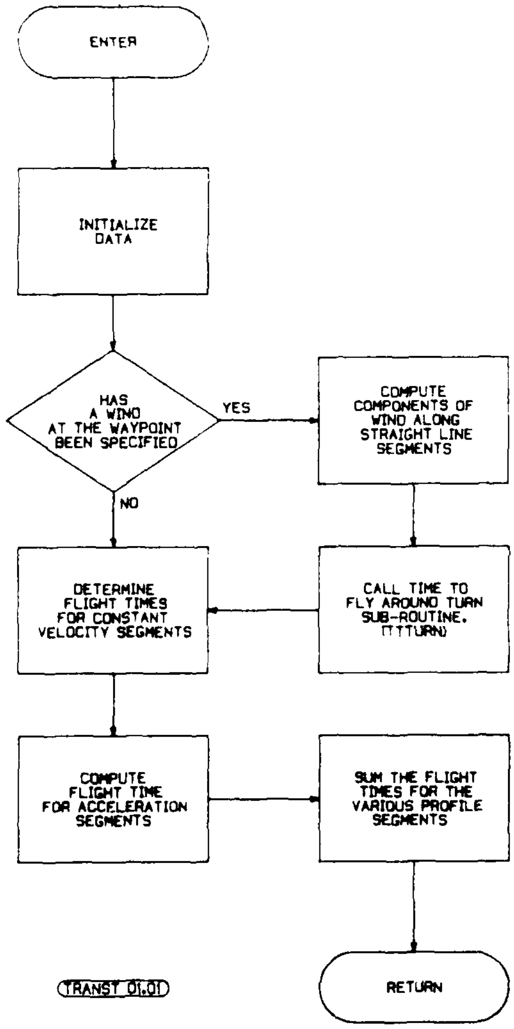
SUBROUTINE SPDLIM (SPEED LIMIT)
FIGURE C-9



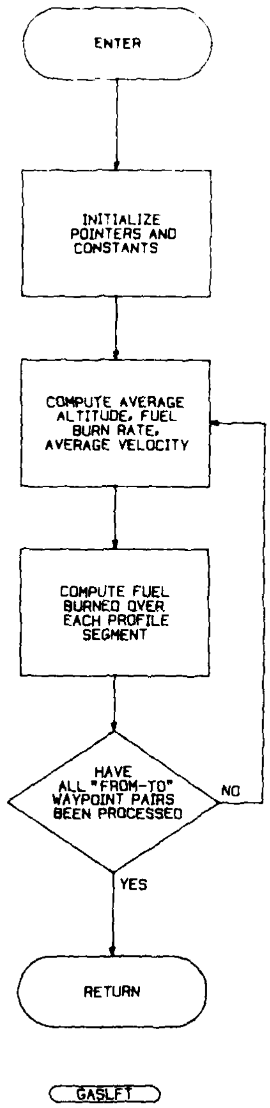
SUBROUTINE NSPD2 (NOMINAL SPEED-2)
FIGURE C-10



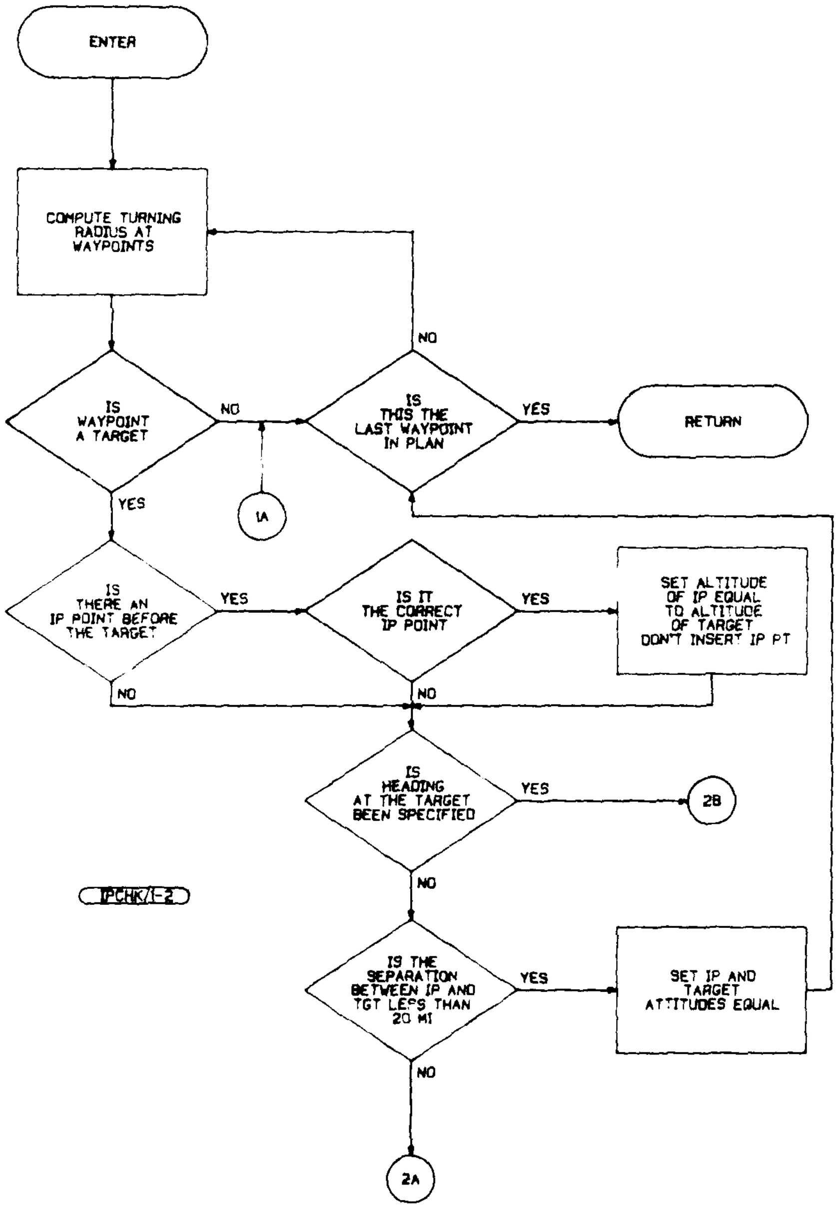
SUBROUTINE TTTURN (TIME-TO-TURN)
FIGURE C-11



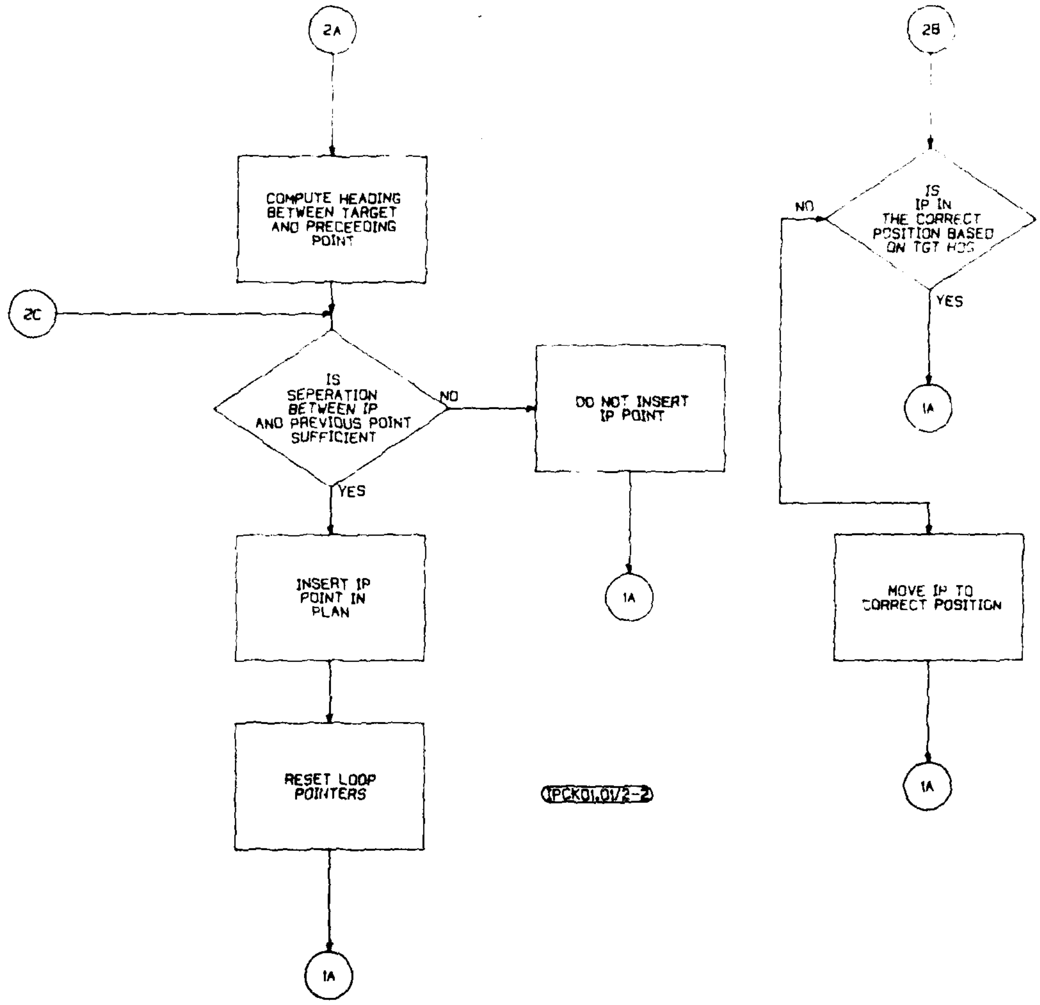
SUBROUTINE TRANST (TRANSIT TIME)
FIGURE C-12



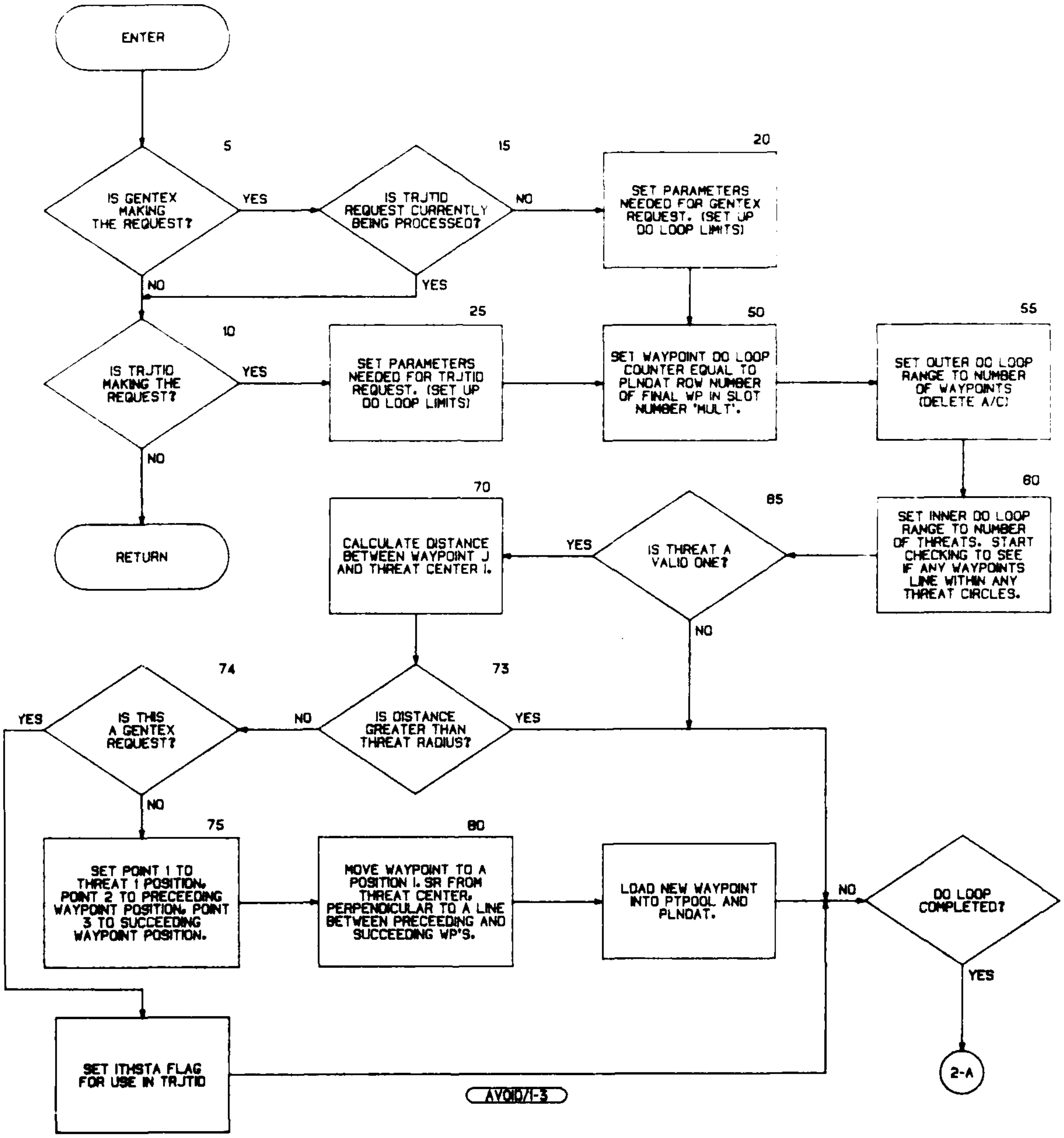
SUBROUTINE GASLFT (FUEL REMAINING)
FIGURE C-13



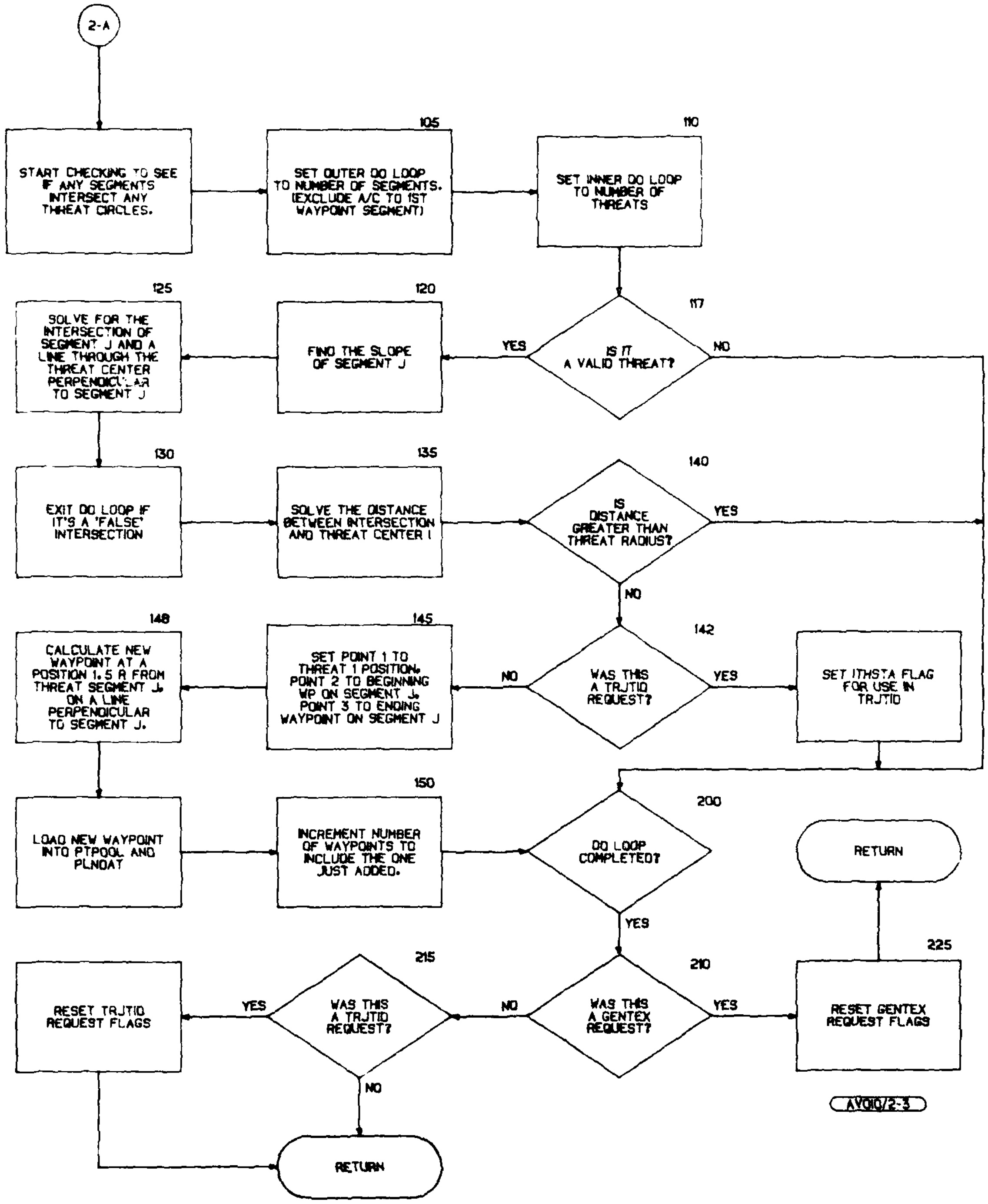
SUBROUTINE IPCHK (TARGET IP CHECK)
FIGURE C-14 (1 of 2)



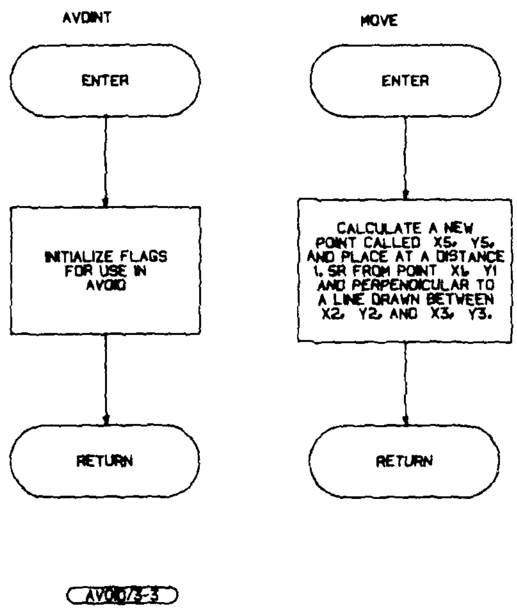
SUBROUTINE IPCHK (TARGET IP CHECK)
FIGURE C-14 (2 of 2)



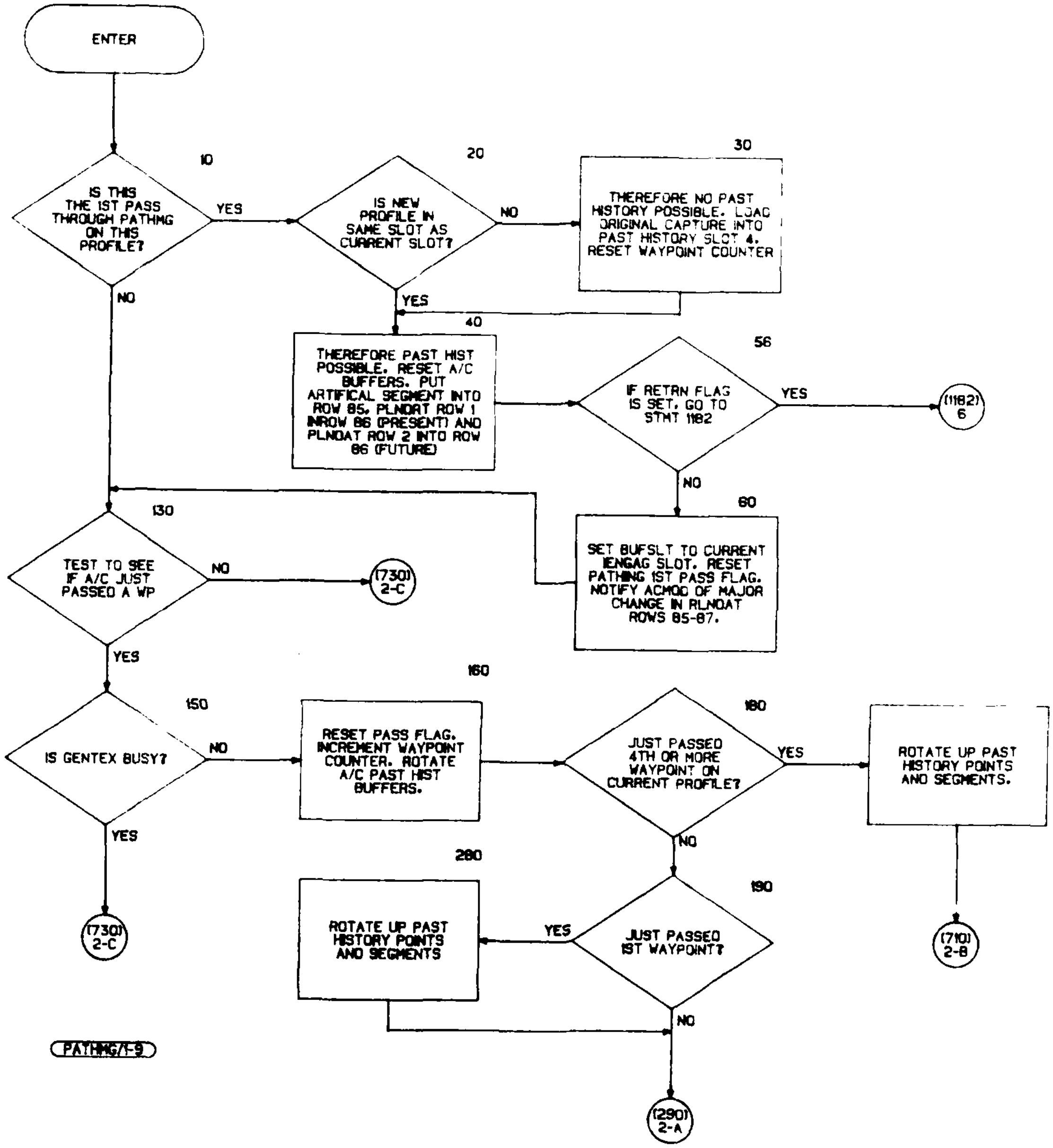
SUBROUTINE AVOID (THREAT AVOIDANCE)
FIGURE C-15 (1 of 3)



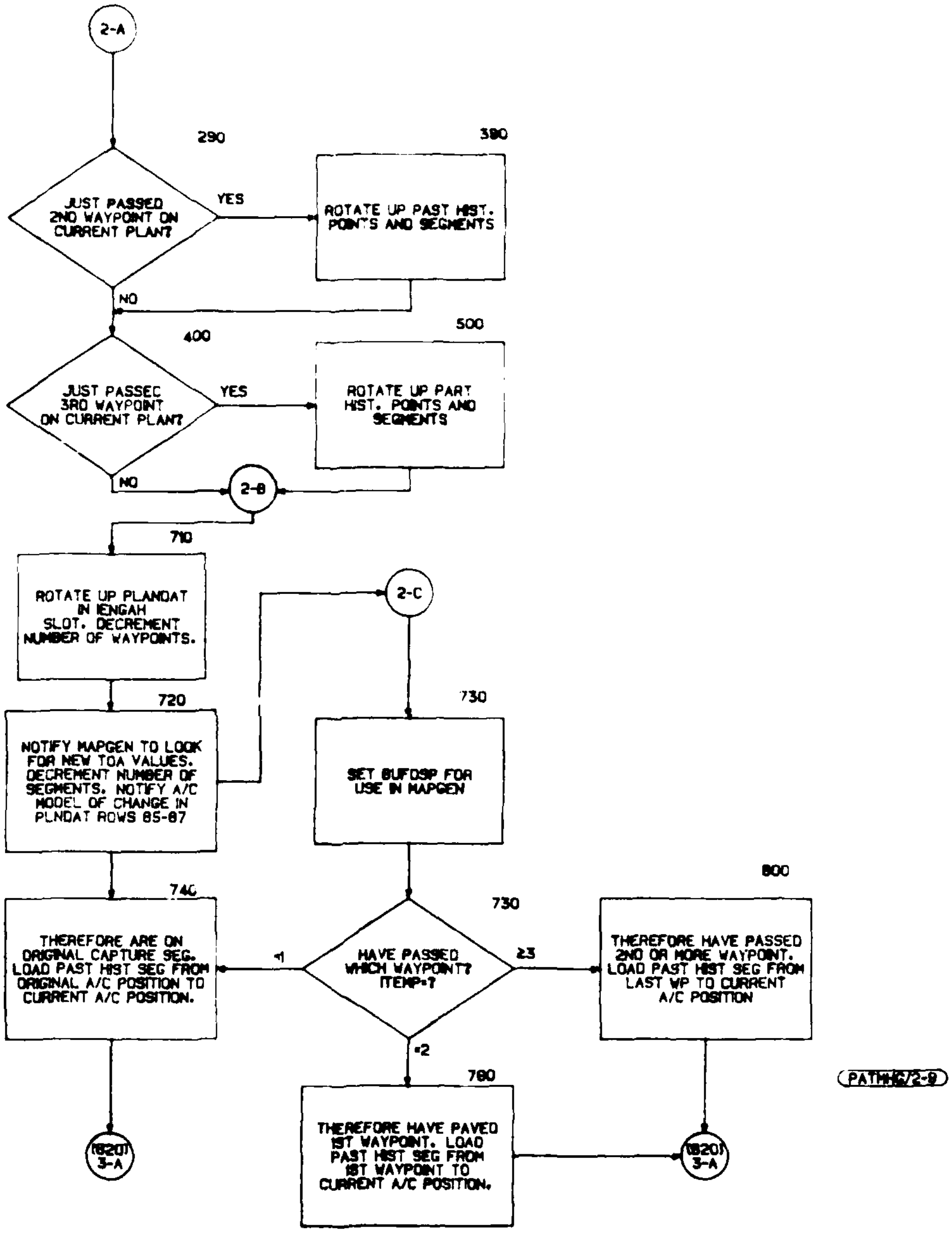
SUBROUTINE AVOID (THREAT AVOIDANCE)
FIGURE C-15 (2 of 3)



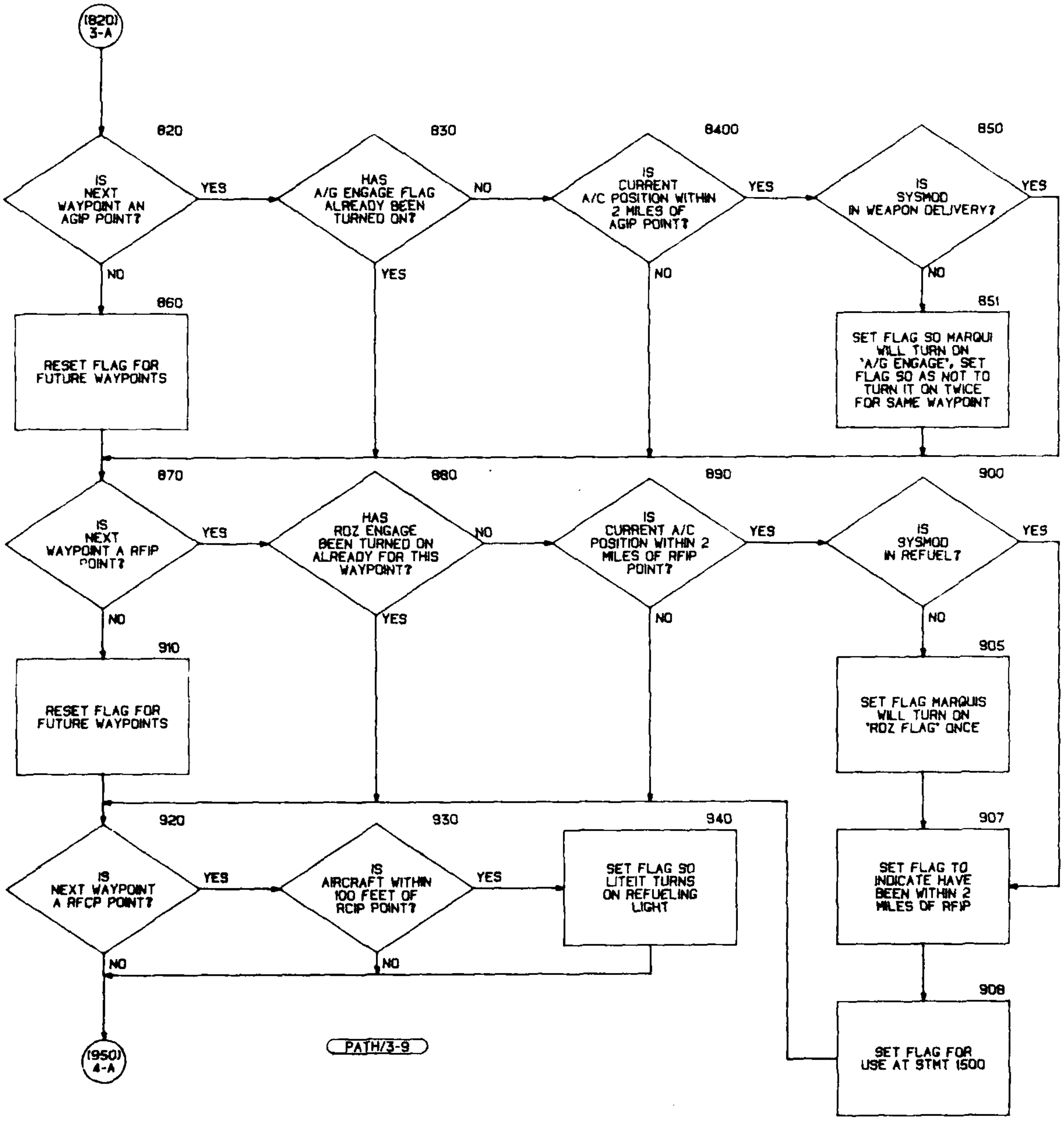
SUBROUTINE AVOID (THREAT AVOIDANCE)
FIGURE C-15 (3 of 3)



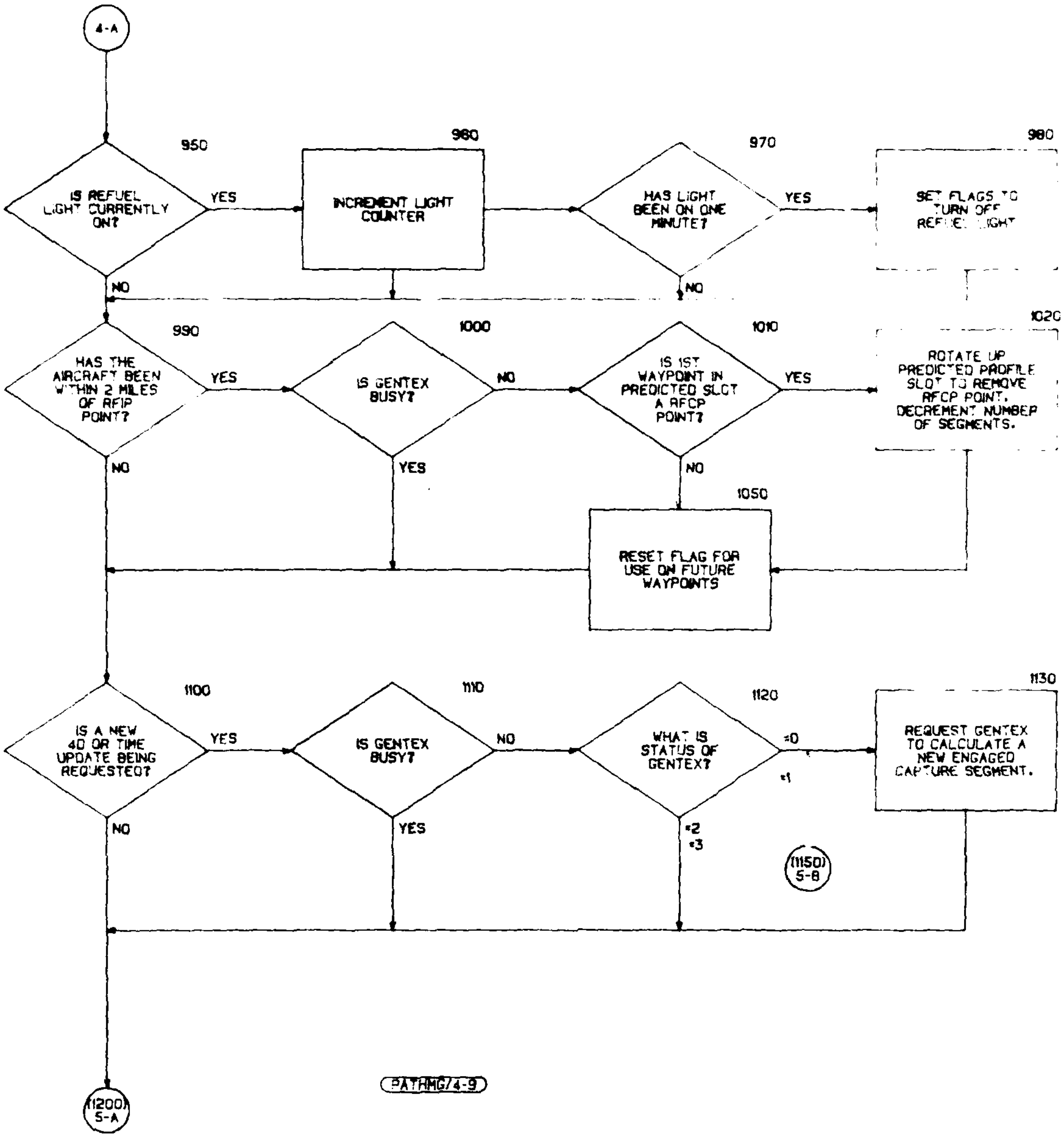
SUBROUTINE PATHMG (PATH MANAGEMENT)
FIGURE C-16 (1 of 9)



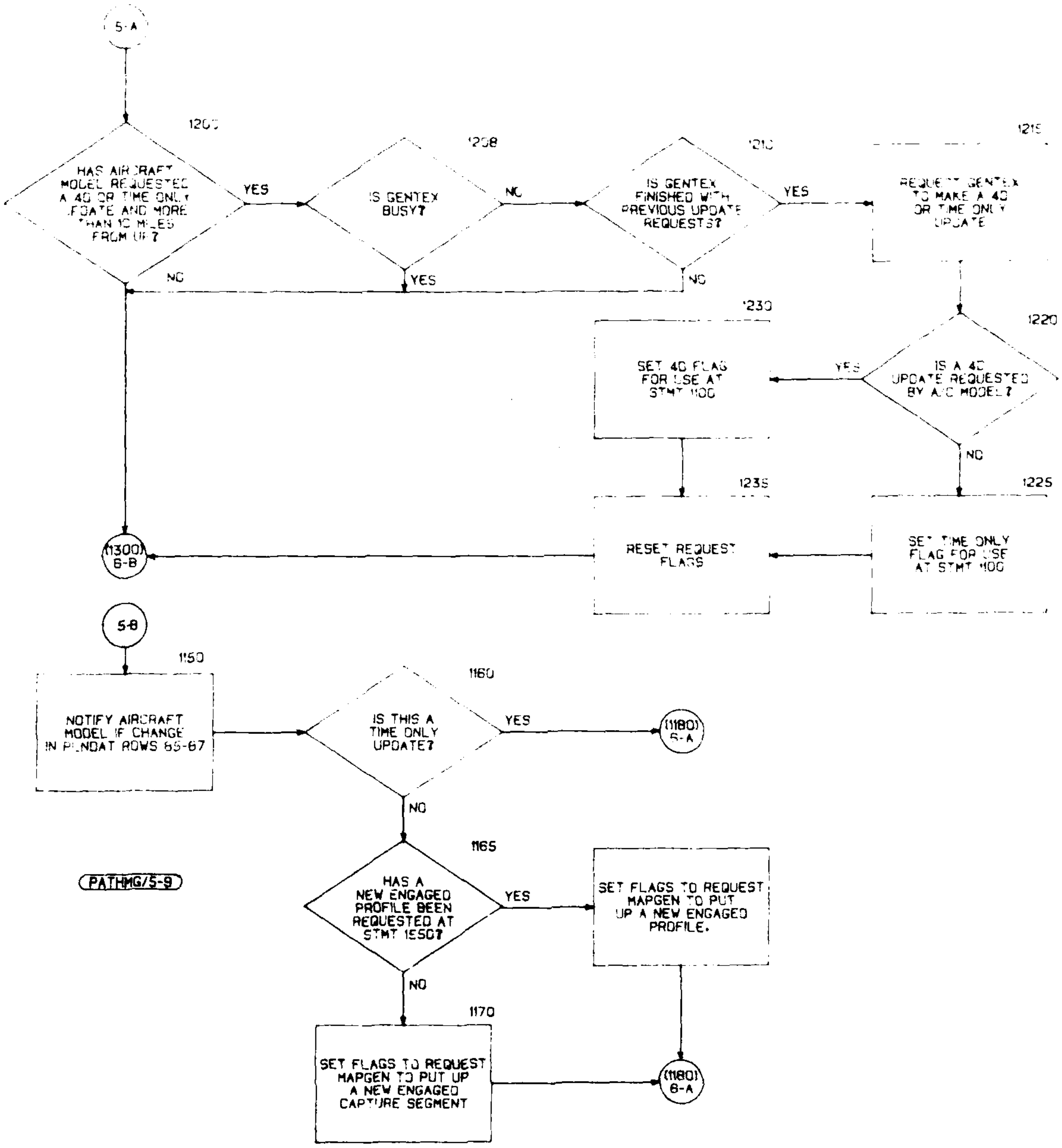
SUBROUTINE PATHMG (PATH MANAGEMENT)
FIGURE C-16 (2 of 9)



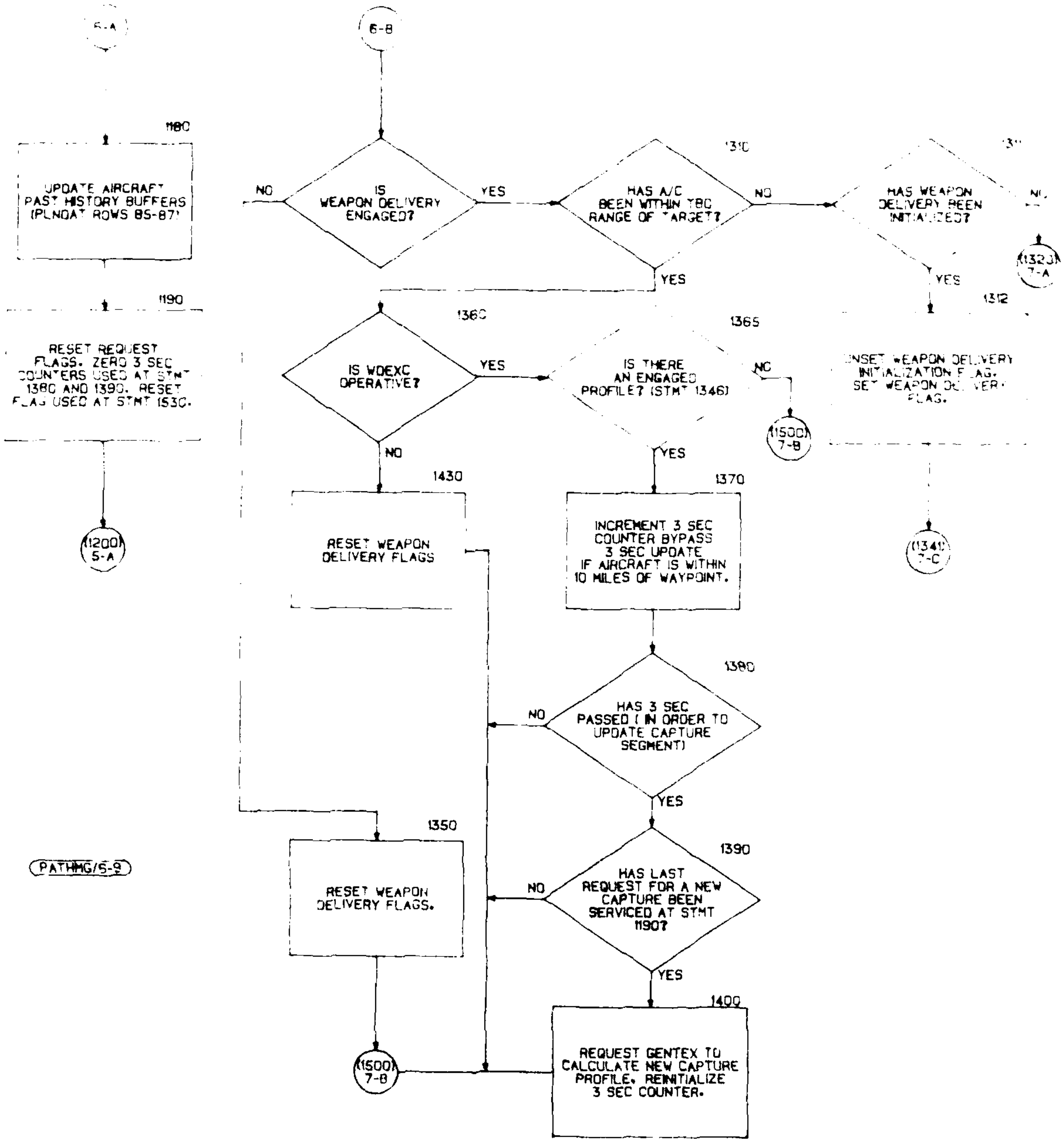
SUBROUTINE PATHMG (PATH MANAGEMENT)
FIGURE C-16 (3 of 9)



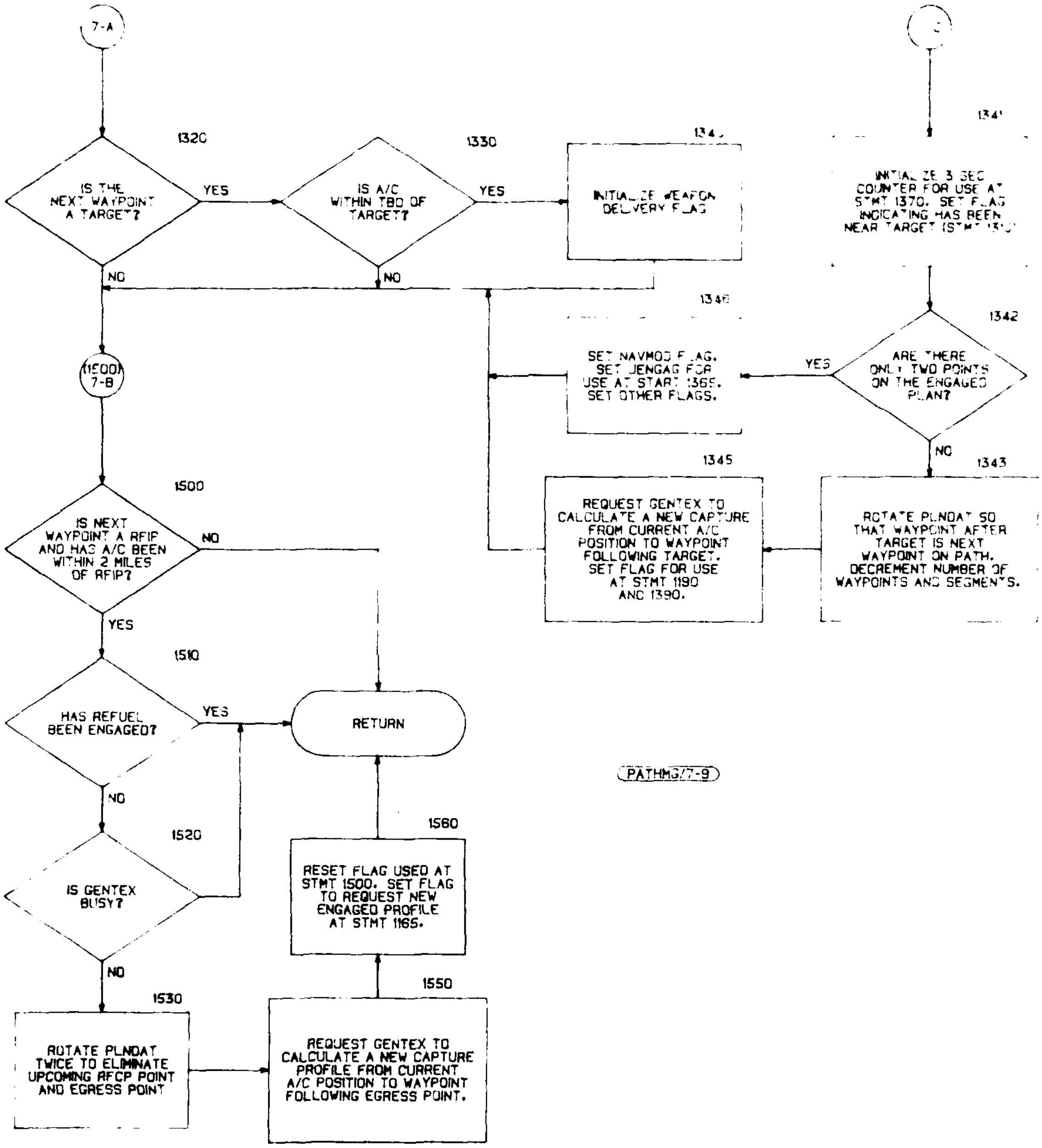
SUBROUTINE PATHMG (PATH MANAGEMENT)
FIGURE C-16 (4 of 9)



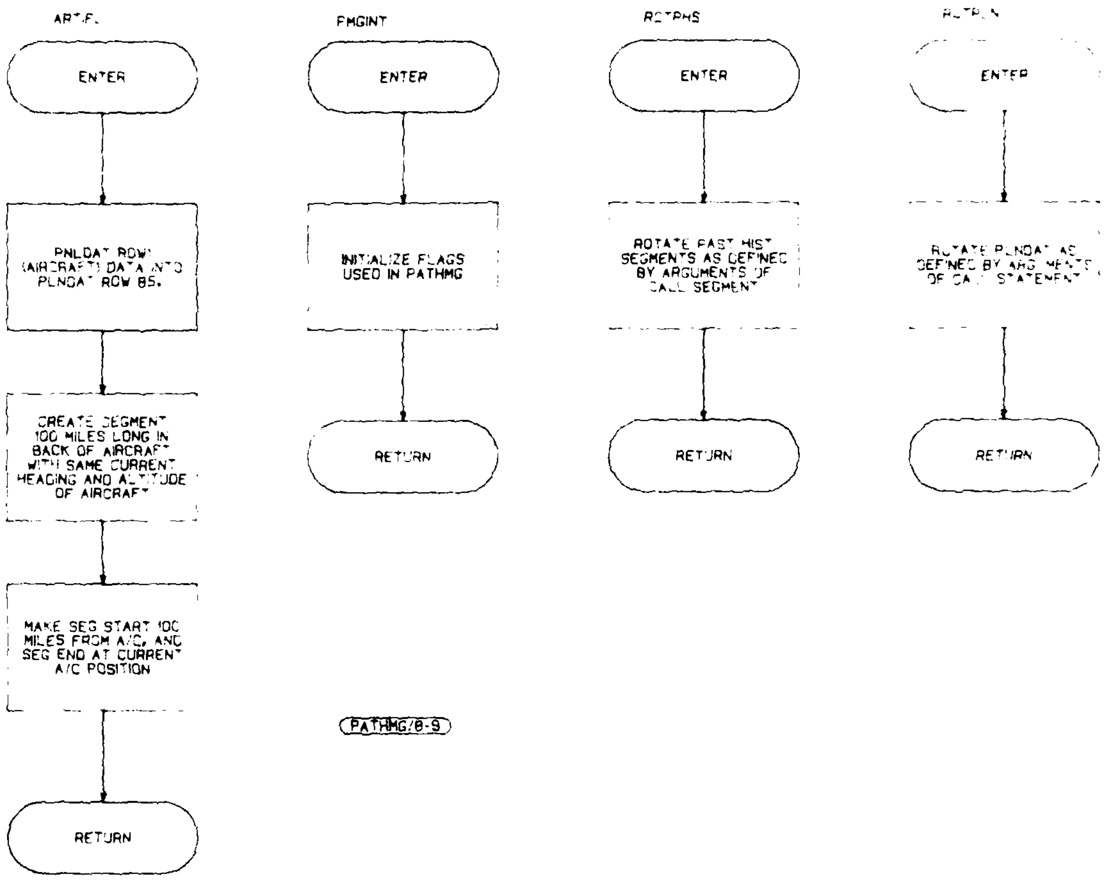
SUBROUTINE PATHMG (PATH MANAGEMENT)
FIGURE C-16 (5 of 9)



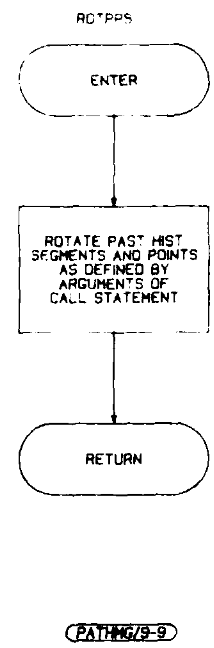
SUBROUTINE PATHMG (PATH MANAGEMENT)
FIGURE C-16 (6 of 9)



SUBROUTINE PATHMG (PATH MANAGEMENT)
FIGURE C-16 (7 of 9)



SUBROUTINE PATHMG (PATH MANAGEMENT)
FIGURE C-16 (8 of 9)



SUBROUTINE PATHMG (PATH MANAGEMENT)
FIGURE C-16 (9 of 9)

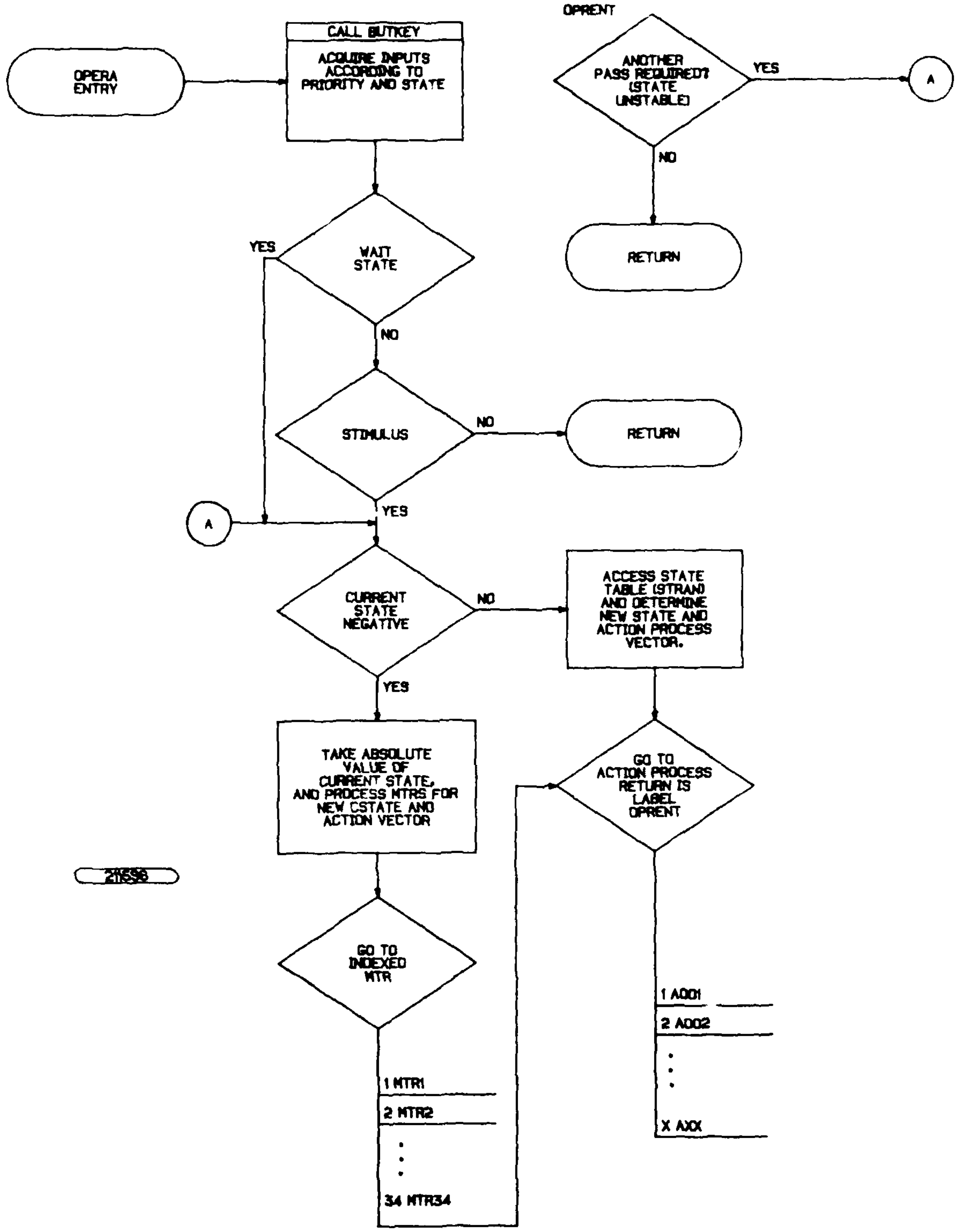
APPENDIX D

CONTROL/DISPLAY FLOW CHARTS AND STATE DIAGRAMS

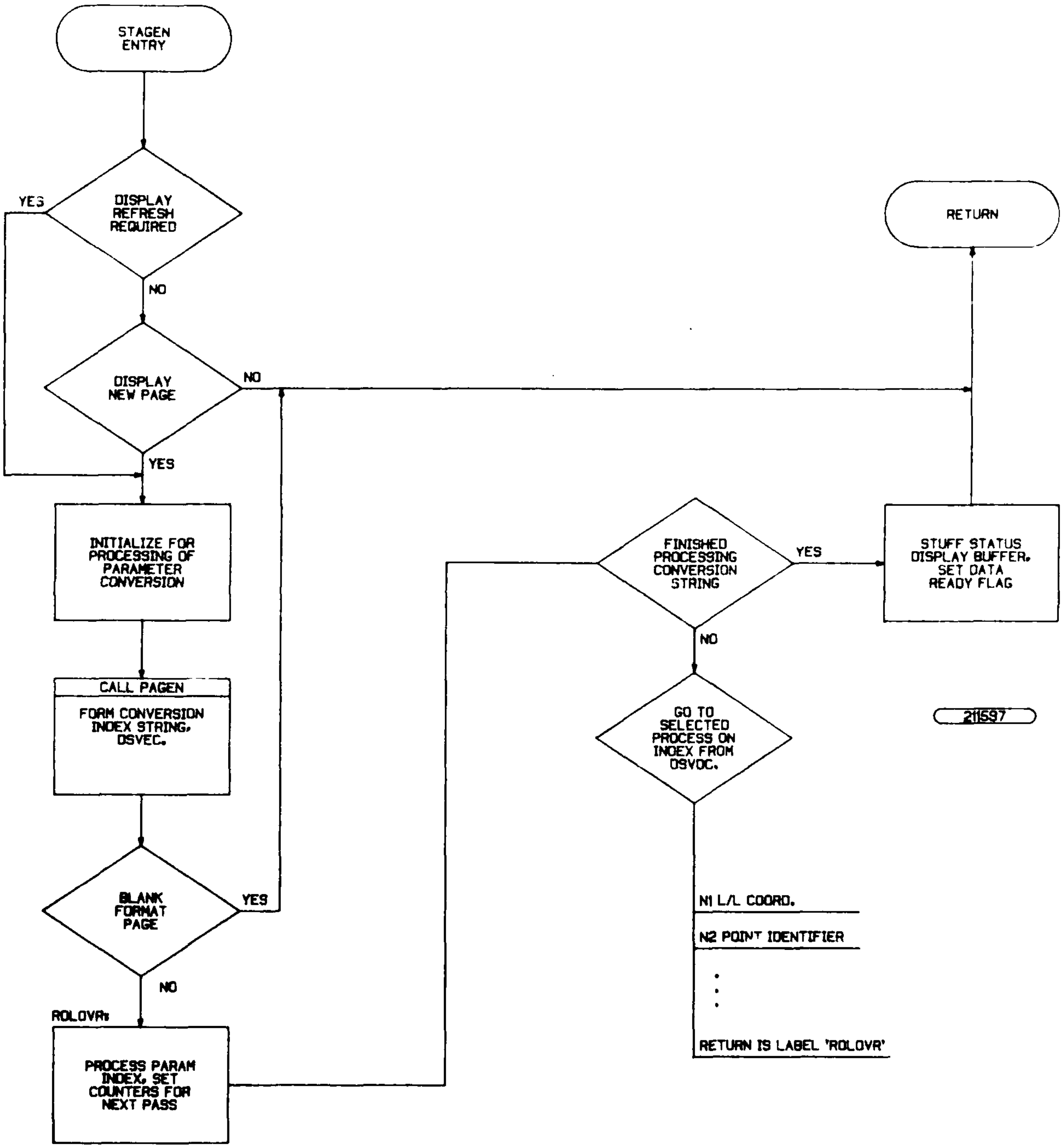
TABLE D-I
MAJOR STATE TRANSITION TABLE (STRAN)

(CSTATE)	STIMULUS (Generally Keys) / STABLE STATE DESC	FLY-TO	CROSS HAIR ON	TARGET	WAY POINT	PAGE DOWN	PAGE	CROSS HAIR INSERT	ENTER	DATA	ENGAGE	WEAPON RELEASE	ENTER ON CROSS HAIR	SPARE	SPARE
1	NAV SELECT	8/8	14/14	27/16	27/17	0/0	0/0	0/0	0/0	MTR28/102	MTR27/43	MTR8/61	0/0		
2	DEPARTURE/APPROACH SELECT	8/8	14/14	27/16	27/17	0/0	0/0	0/0	0/0	0/0	0/0	MTR8/61	0/0		
3	RENDEZVOUS SELECT	8/8	14/14	27/16	27/17	0/0	0/0	0/0	0/0	0/0	0/0	MTR8/61	0/0		
4	BLIND WEAPON DELIVERY SELECT	8/8	14/14	27/16	27/17	0/0	0/0	0/0	4/112	MTR18/65	MTR33/66	MTR8/61	0/0		
5	NAV PLAN DATA	8/8	14/14	27/16	27/17	5/115	5/115	0/0	MTR2/30	MTR31/31	0/0	MTR8/61	0/0		
6	DEPARTURE/APPROACH DATA	0/0	0/14	0/16	0/0	0/0	0/0	0/0	0/0	0/0	0/0	MTR8/61	0/0		
7	PILOT RELIEF SELECT	8/8	14/14	27/16	27/17	0/0	0/0	0/0	1/104	0/0	0/0	MTR8/61	0/0		
8	FLY-TO DISPLAY	8/8	0/0	27/16	27/17	0/0	0/0	MTR5/109	MTR5/109	0/0	0/0	MTR8/61	999/116		
9	HOLD PATTERN SELECT	8/8	14/14	27/16	27/17	0/0	0/0	0/0	0/0	0/0	0/0	MTR8/61	0/0		
10	CLUTTER SELECT	8/8	14/14	27/16	27/17	0/0	0/0	0/0	999/46	0/0	0/0	MTR8/61	0/0		
11	PLAN DISPLAY (NO EDIT)	8/8	14/14	27/16	27/17	/35	/39	0/0	0/0	0/0	0/0	MTR8/61	0/0		
12	MARK DISPLAY	8/8	14/14	27/16	27/17	0/0	0/0	0/0	0/0	0/0	0/0	MTR8/61	0/0		
13	DATA LINK DISPLAY (JTID)	8/8	14/14	27/16	27/17	0/0	0/0	0/0	0/0	0/0	0/0	MTR8/61	0/0		
14	X-HAIR INITIALIZE	8/8	0/0	27/16	27/17	0/0	0/0	MTR15/110	0/0	MTR32/114	0/0	MTR8/61	999/116		
15	PLAN MODE (FROM KEY)	8/8	14/14	27/16	27/17	0/0	0/0	0/0	0/0	0/0	0/0	MTR8/61	0/0		
16	DESIGNATED POINT PAGE	8/8	16/33	27/16	27/17	16/108	16/108	MTR30/57	MTR30/57	0/0	0/0	MTR8/61	0/0		
17	DESIGNATED POINT FROM PLAN	8/8	17/33	27/16	27/17	17/108	17/107	MTR9/49	MTR9/49	0/0	0/0	MTR8/61	999/116		
18	SUPER INDEX SELECT	8/8	14/14	27/16	27/17	0/0	0/0	0/0	0/0	MTR4/87	0/0	MTR8/61	0/0		
19	BLANK THREAT	8/8	19/117	27/16	27/17	19/92	19/93	0/0	0/0	0/0	0/0	MTR8/61	0/0		
20	PRE-FLIGHT CHECK LIST	8/8	14/14	27/16	27/17	0/0	0/0	0/0	0/0	0/0	0/0	MTR8/61	0/0		
21	FLIGHT DISPLAY	8/8	14/14	27/16	27/17	0/0	0/0	0/0	0/0	0/0	0/0	MTR8/61	0/0		
22	POINT INDEX SELECT	8/8	14/14	27/16	27/17	22/38	22/38	0/0	0/0	MTR26/40	0/0	MTR8/61	0/0		
23	PLAN INDEX SELECT	8/8	14/14	27/16	27/17	0/0	0/0	0/0	0/0	11/88	0/0	MTR8/61	0/0		
24	POINT, LOOK AND ENTER	8/8	24/91	27/16	27/17	24/92	24/93	0/0	0/0	0/0	0/0	MTR8/61	0/0		
25	DESIGNATED COUPLE POINT	8/8	25/0	27/16	27/17	0/0	0/0	0/0	0/0	0/0	0/0	MTR8/61	0/0		
26	REFUEL IP/CP PATTERN	8/8	26/0	27/16	27/17	0/0	0/0	0/0	0/0	0/0	0/0	MTR8/61	0/0		
27	NON-DESIGNATED POINT	8/8	27/91	27/16	27/17	27/92	27/93	MTR14/55	MTR14/55	[illegible]	0/0	MTR8/61	999/116		
28		8/8	14/14	27/16	27/17	0/0	0/0	0/0	0/0	0/0	0/0	MTR8/61	0/0		
29	SPARE														
30	SPARE														

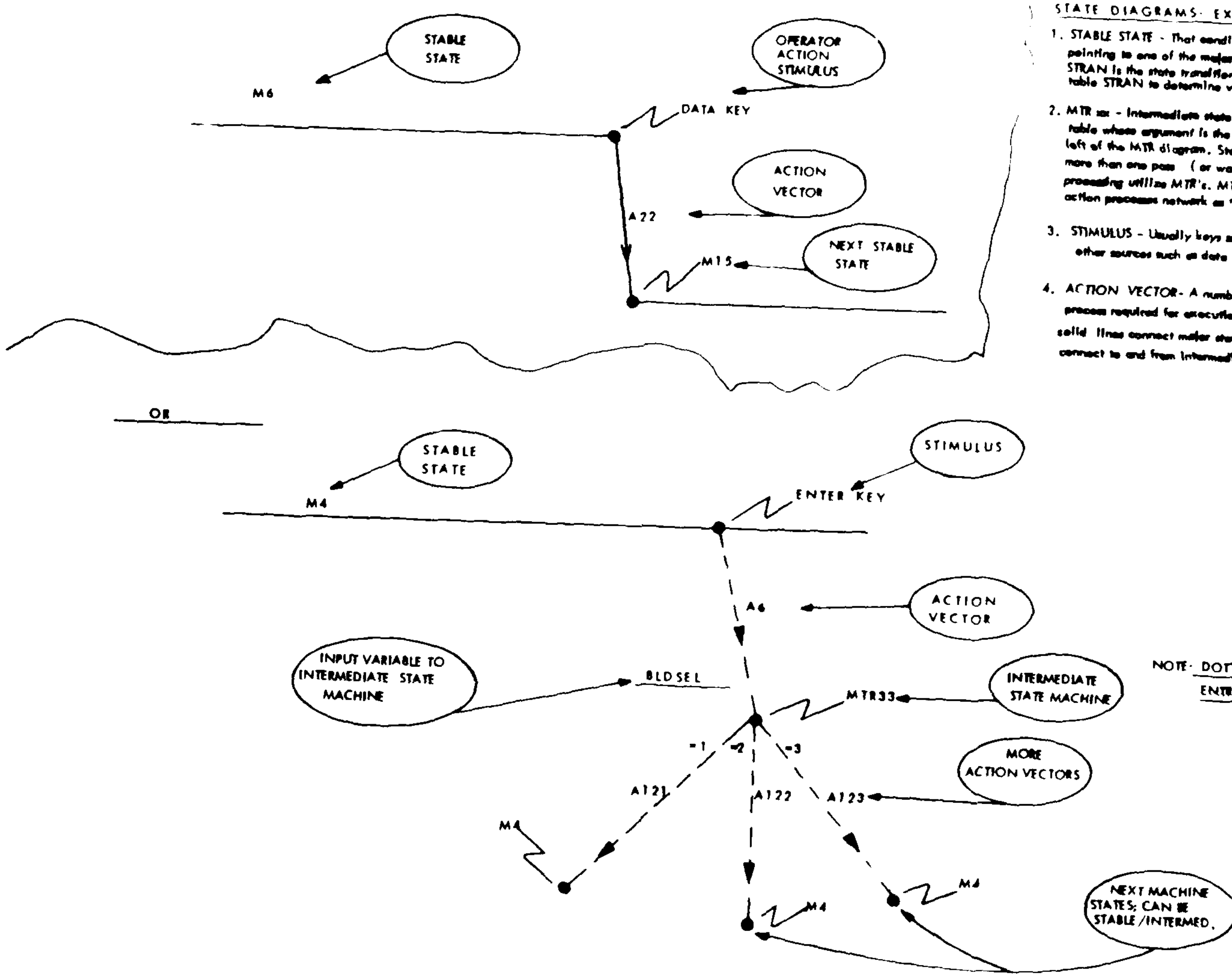
TABLE D-I This is the Major State Transition table (STRAN). STRAN is used by the [illegible]
The rows represent the major states of the system; the columns represent [illegible] that may affect the system.
The intersections contain the next state and the action process [illegible] the next state.



OPERA FLOW CHART
FIGURE D-1



SUBROUTINE STAGEN
FIGURE D-2



STATE DIAGRAMS: EXAMPLES & EXPLANATIONS

1. STABLE STATE - That condition in which the state machine is pointing to one of the major states of the table STRAN (a row). STRAN is the state transition table D-1 identified by Mx. Use table STRAN to determine valid state for a particular stimulus.

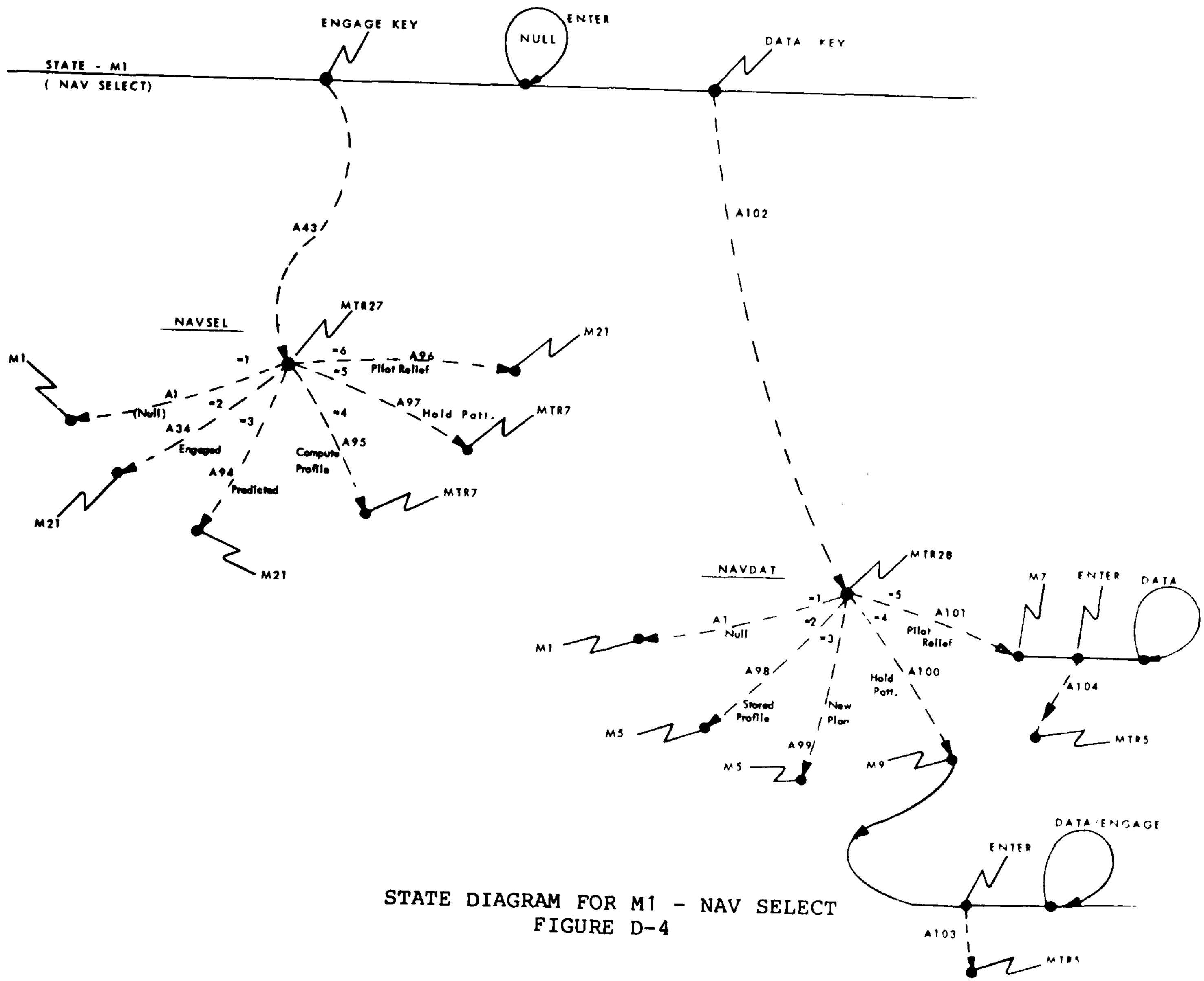
2. MTR xx - Intermediate state machine. A minor state transition table whose argument is the input variable located at the upper left of the MTR diagram. State machine operations which require more than one pass (or wait cycles) during control/display processing utilize MTR's. MTR's use the same state processor and action processes network as the major state machine, STRAN.

3. STIMULUS - Usually keys selected by the operator can be from other sources such as data - link or bomb release.

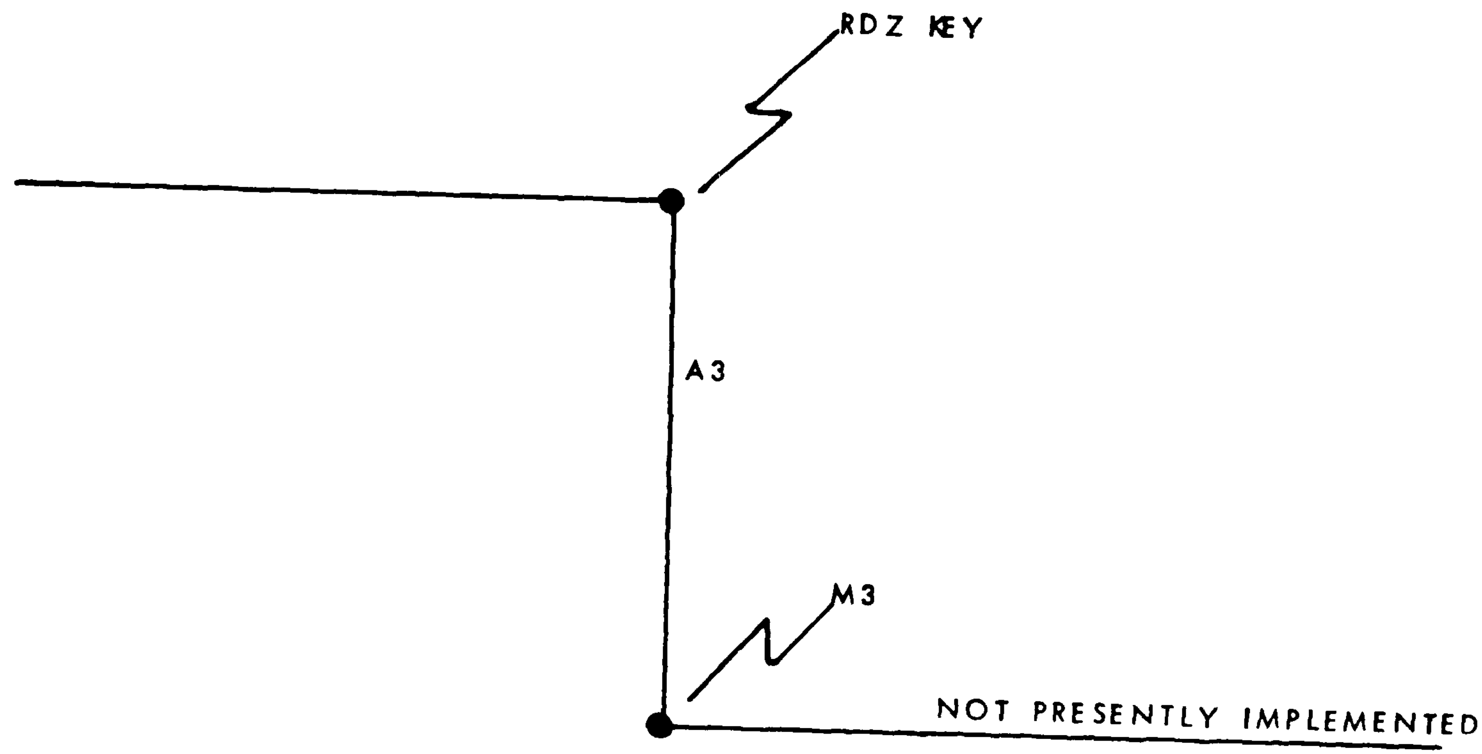
4. ACTION VECTOR - A number identifying the control/display process required for execution before moving to the next state. solid lines connect major states (Mx), whereas dotted lines connect to and from intermediate states.

NOTE: DOTTED LINES INDICATE ENTRY OR EXIT FROM MTR

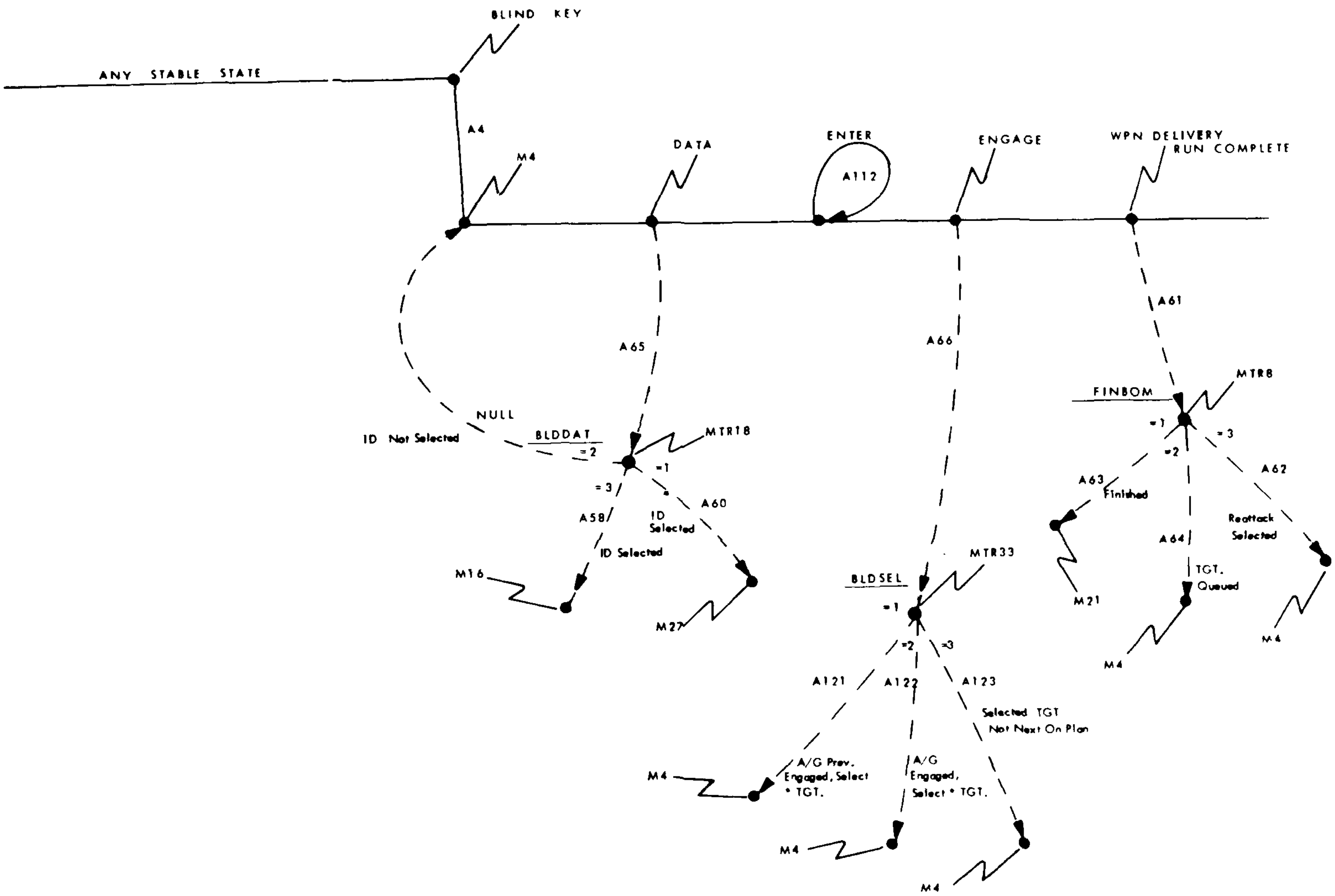
SAMPLE MACHINE STATE DIAGRAM
FIGURE D-3



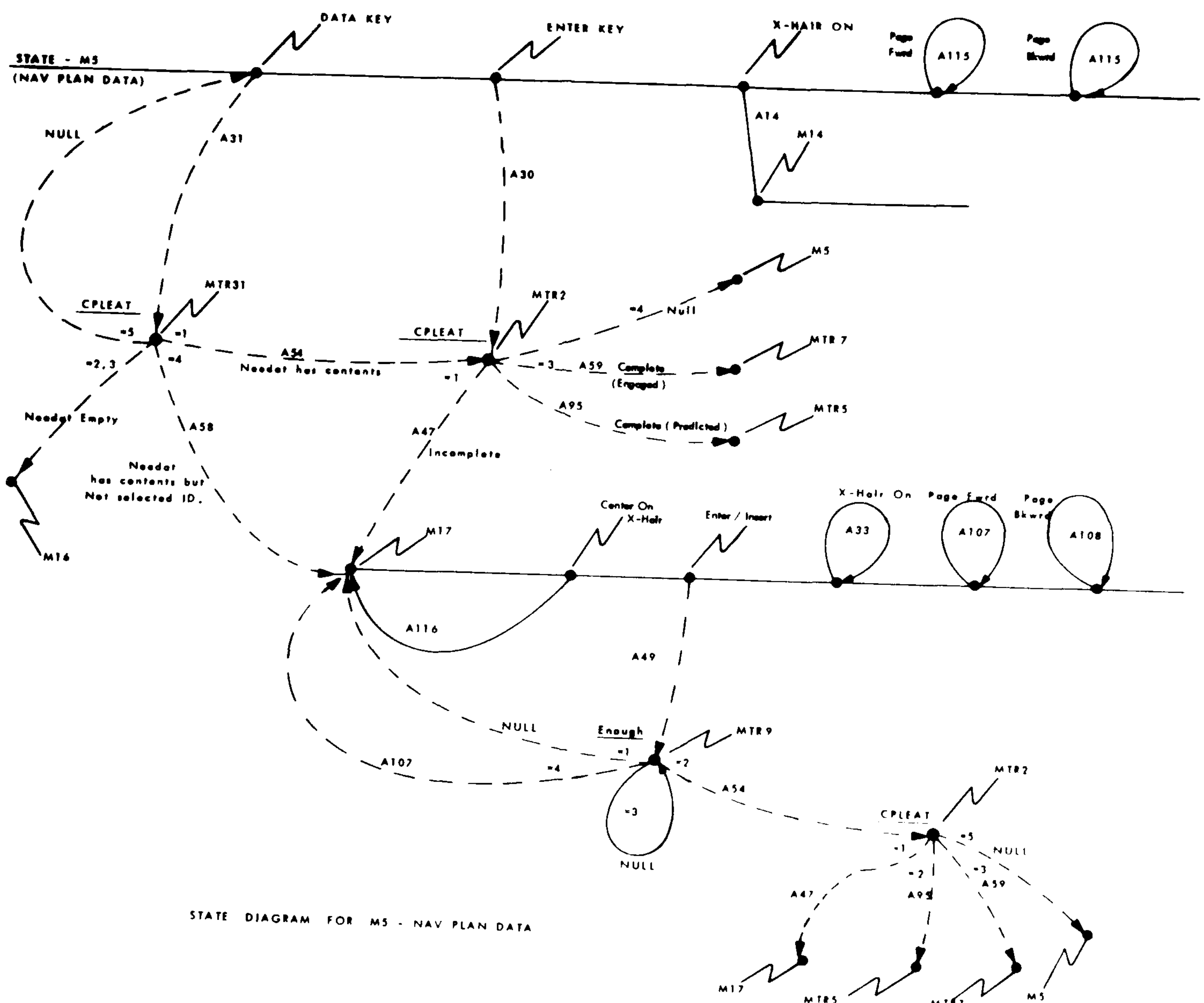
STATE DIAGRAM FOR M1 - NAV SELECT
FIGURE D-4



STATE DIAGRAM FOR RENDEZVOUS KEY
FIGURE D-5

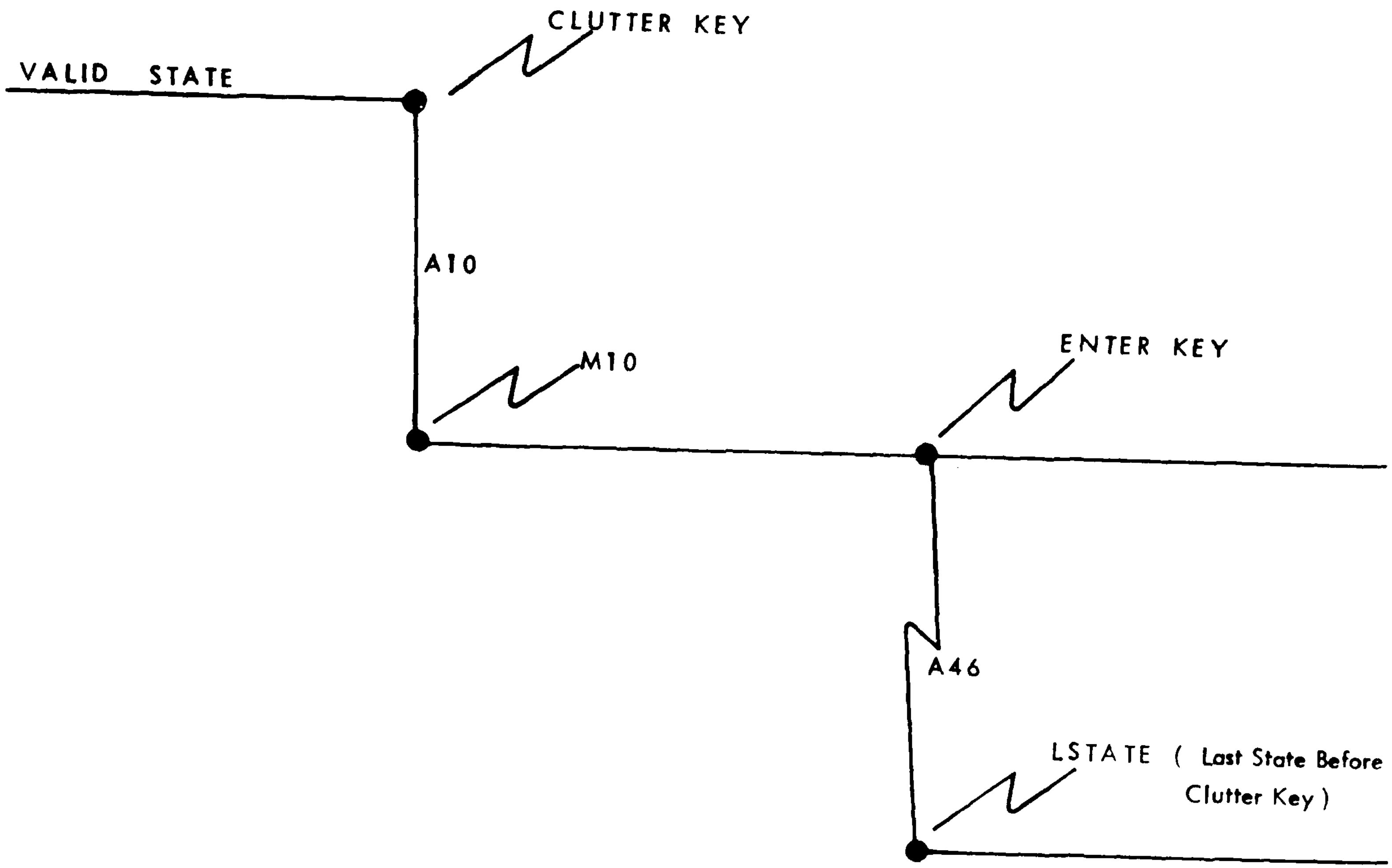


STATE DIAGRAM FOR BLIND (BOMBING) KEY
FIGURE D-6

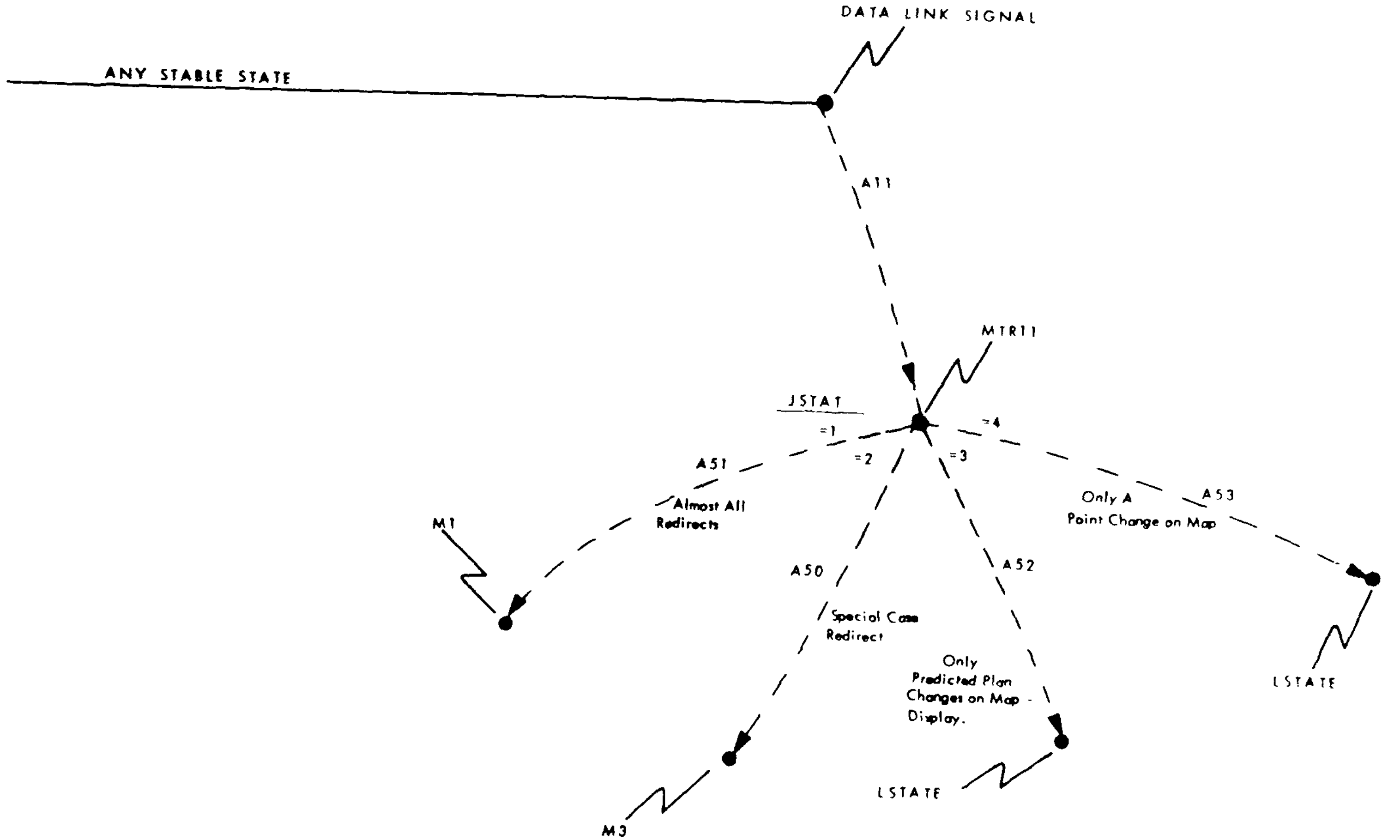


STATE DIAGRAM FOR M5 - NAV PLAN DATA

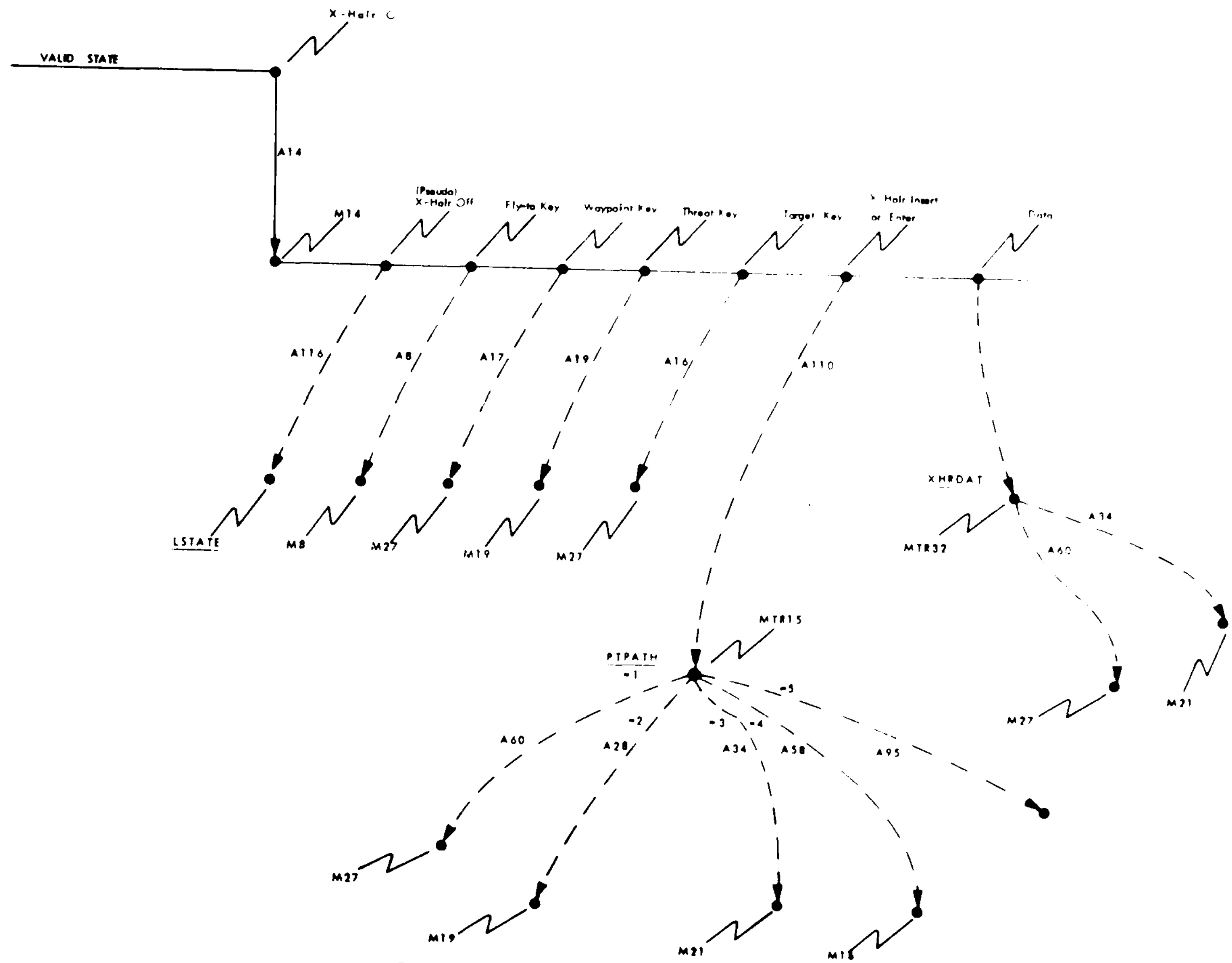
STATE DIAGRAM FOR M5 - NAV PLAN DATA
FIGURE D-7



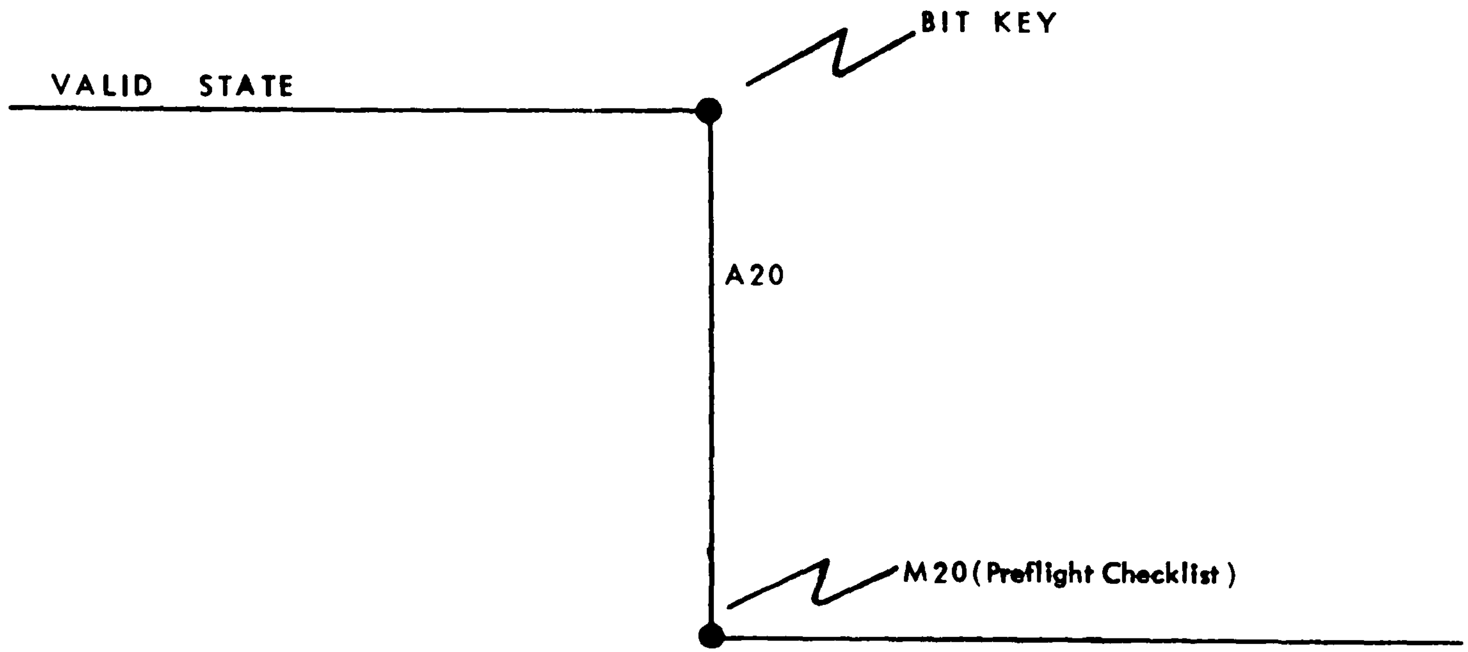
STATE DIAGRAM FOR CLUTTER KEY
FIGURE D-8



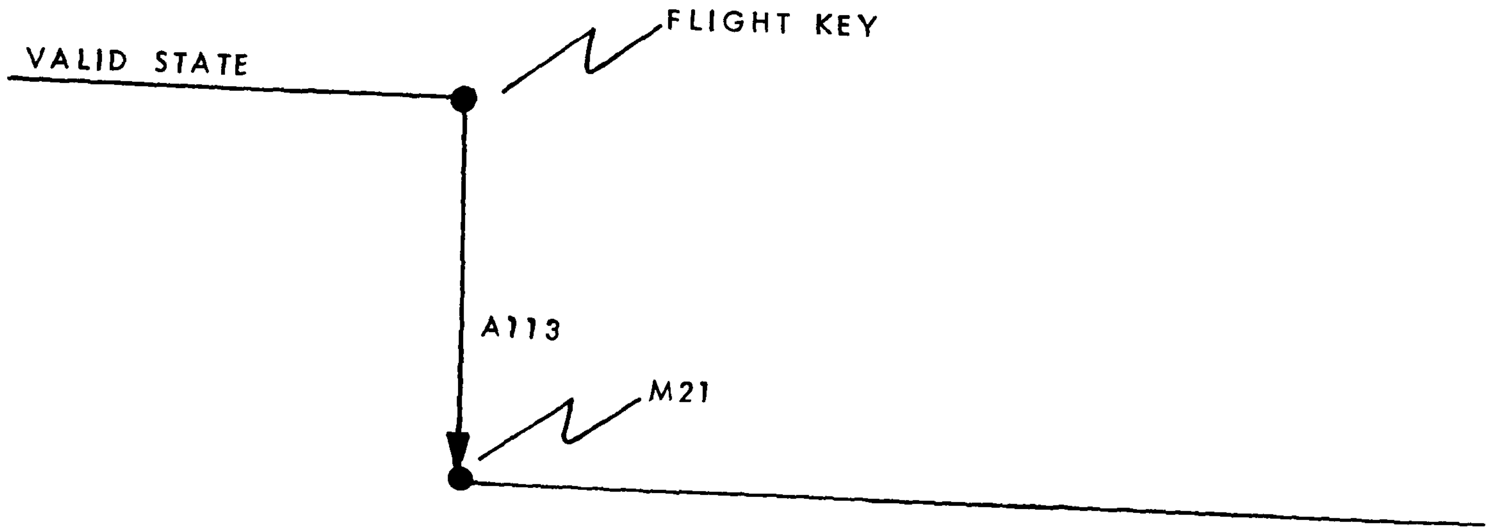
STATE DIAGRAM FOR DATA LINK SIGNAL
FIGURE D-9



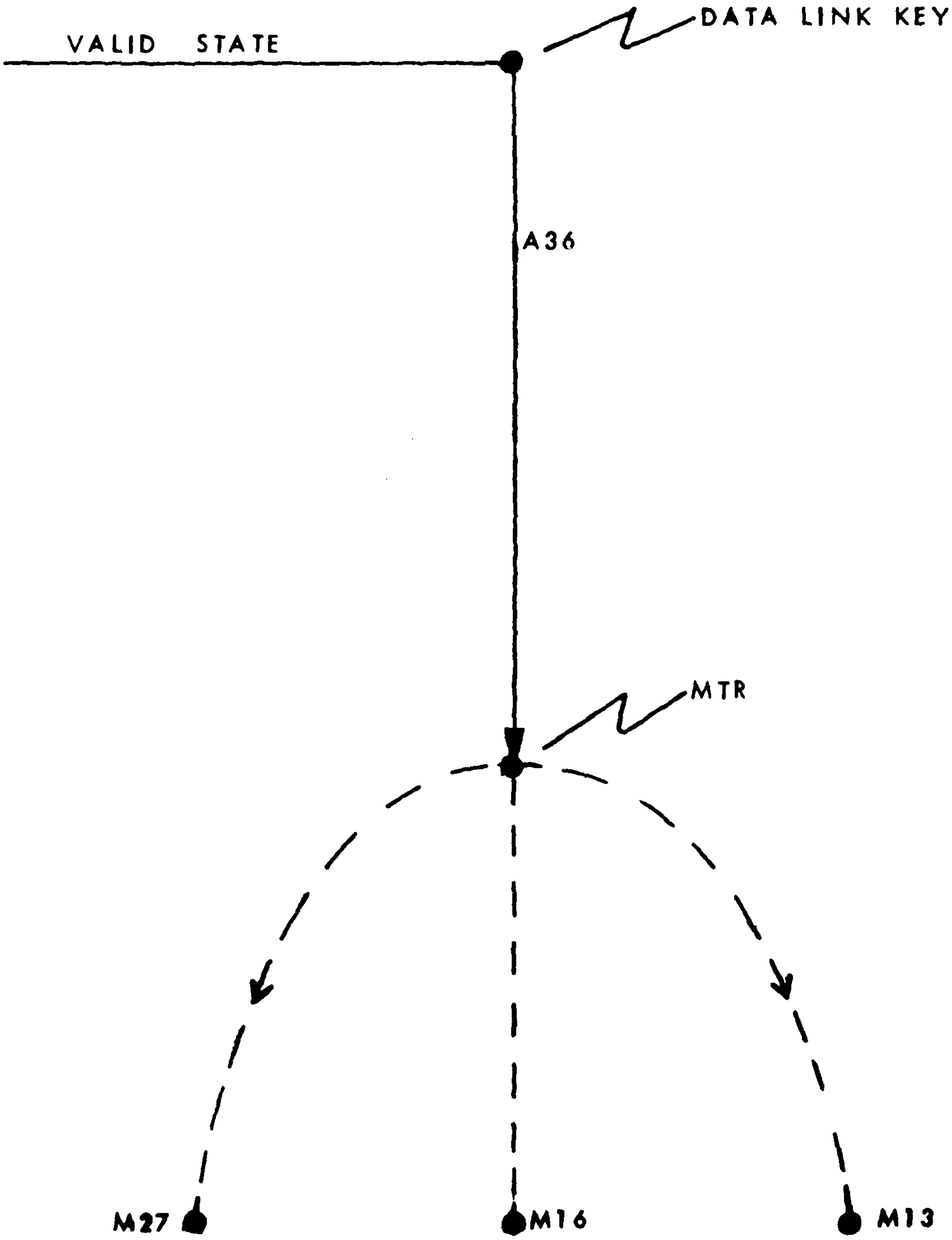
STATE DIAGRAM FOR X-HAIR OPERATION
FIGURE D-10



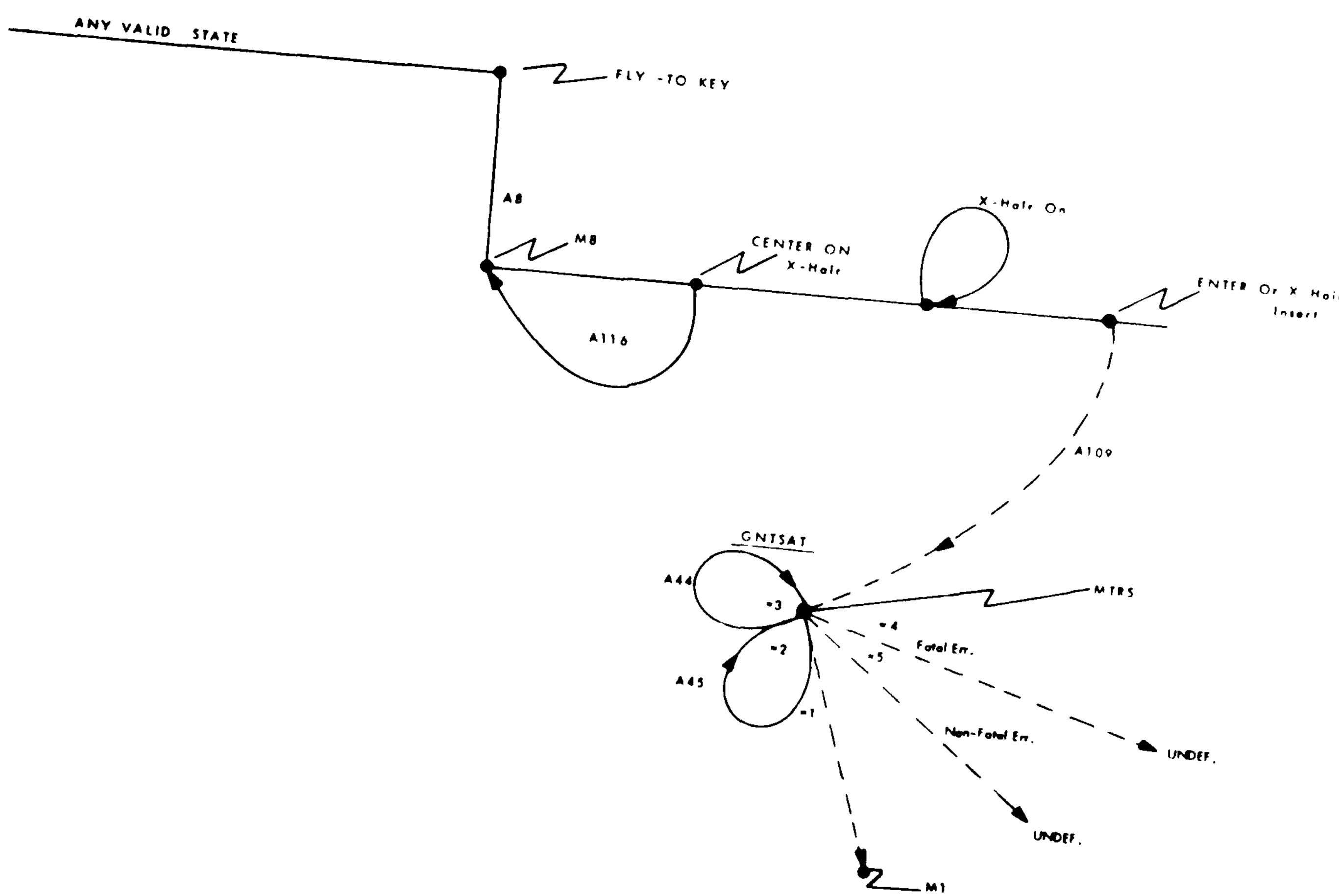
STATE DIAGRAM FOR BIT KEY
FIGURE D-11



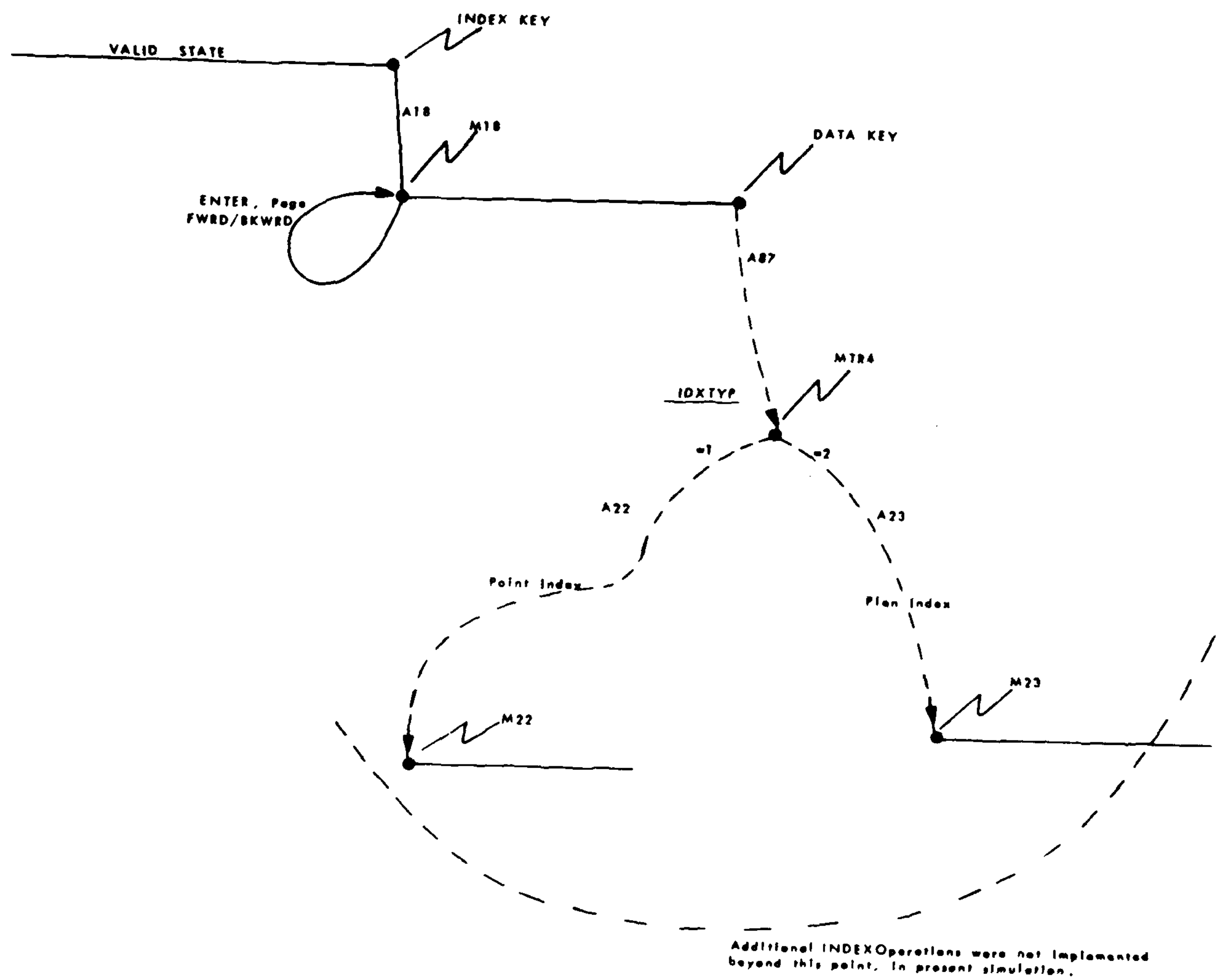
STATE DIAGRAM FOR FLIGHT KEY
FIGURE D-12



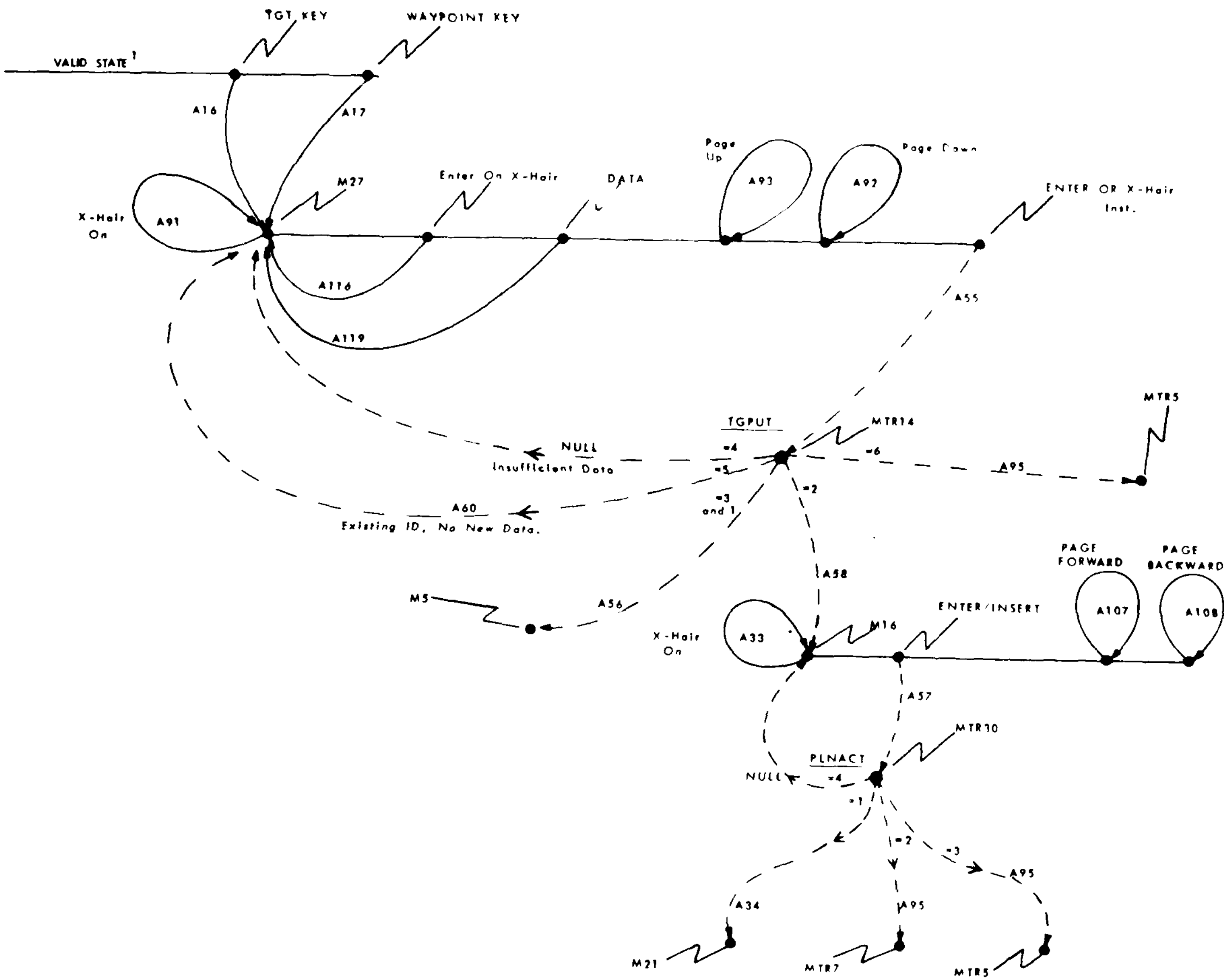
STATE DIAGRAM FOR DATA LINK KEY
FIGURE D-13



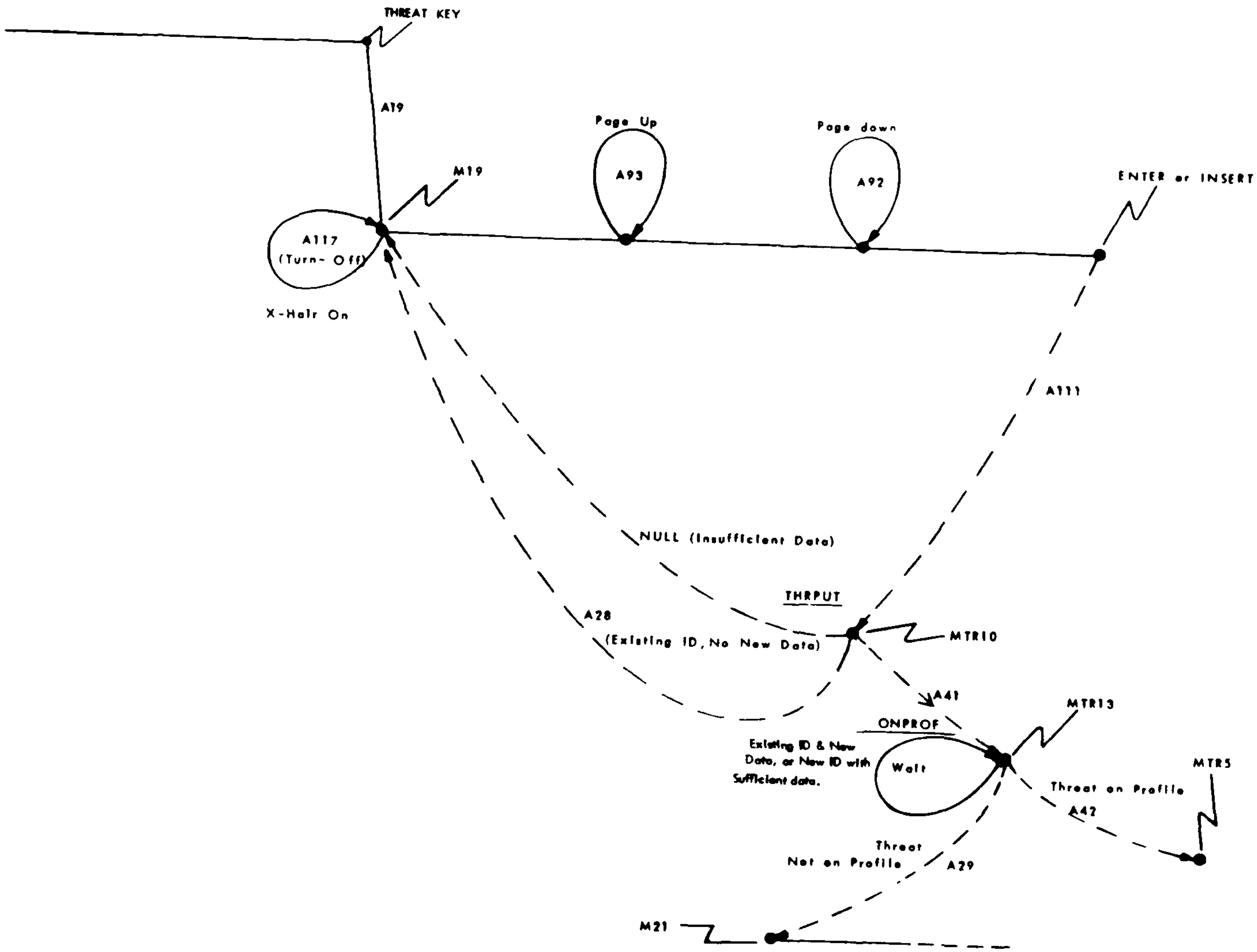
STATE DIAGRAM FOR FLY-TO KEY
FIGURE D-14



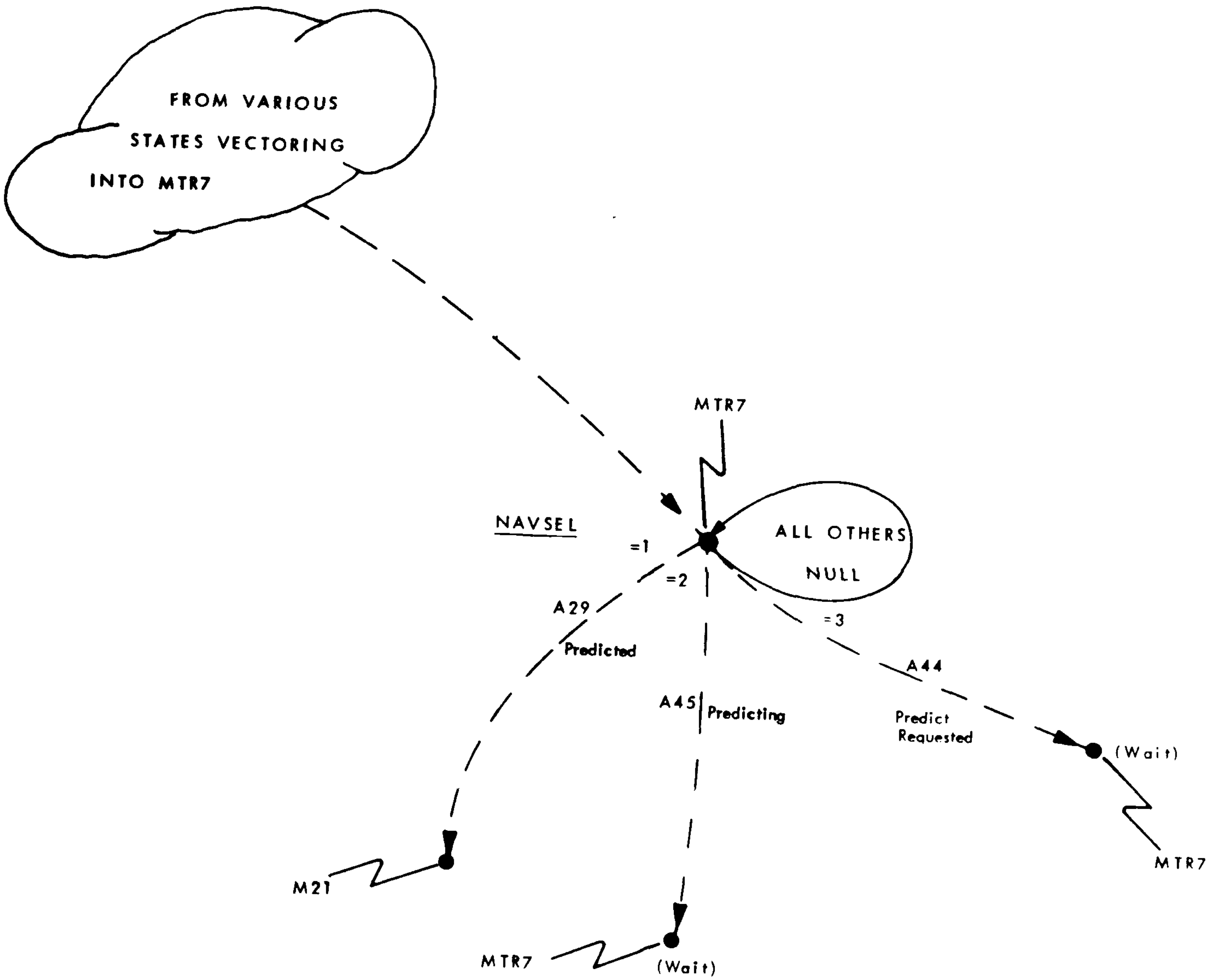
STATE DIAGRAM FOR INDEX OPERATION
FIGURE D-15



STATE DIAGRAM FOR TARGET AND WAYPOINT KEYS
FIGURE D-16



STATE DIAGRAM FOR THREAT KEY
FIGURE D-17



STATE DIAGRAM FOR INTERMEDIATE STATE MACHINE - MTR7
FIGURE D-18

TABLE D-II (1 of 14)
INTERMEDIATE STATE TRANSITION TABLES

State machine
MTR1

<u>Input on top row</u>

STIM - Cockpit keycodes for those listed across...

NAV	T/O,LND	RDZ	BLIND	DECLUT	MARK	JTID	BIT	DATALINK	PLAN MOD	INDEX	THREAT	FLT
M1	M1	M3	M4	M10	M12	MTR11	M20	M13	M15	M18	M19	M21
A1	A1	A3	A4	A10	A12	A11	A20	A36	A32	A18	A19	A113

State Machine
MTR2

Input: CPLEAT

1 = Data incomplete
2 = Data complete; predicted plan
3 = Data complete; engaged plan

1	2	3	4
M17	MTR5	MTR7	M5
A47	A95	A59	0

State machine
MTR4

Input: IDXTYP

1 = Point
2 = Plan

1	2
M22	M23
A22	A23

TABLE D-II (2 of 14)
INTERMEDIATE STATE TRANSITION TABLES

State Machine
MTR5

Input: GNTSTAT
1 = Plan is predicted
2 = Predicting
3 = Not Predicted
4 = Fatal error (SPARE)
5 = Non-fatal error (SPARE)

1	2	3	4	5
M1	MTR5	MTR5	MTR2	XXXX
A37	A45	A44	A^{nn}	A^{nn}

State Machine
MTR7

INPUT: GNTSAT
1-5 <see MTR5 >

1	2	3	4	5
M21	MTR7	MTR7	XXXX	XXXX
A29	A45	A44	A^{nn}	A^{nn}

INTERMEDIATE STATE TRANSITION TABLES

State Machine
MTR8

Input: FINBOM
1 = Finished bombing
2 = Next target queued
3 = Reattack

1	2	3
M21	M4	M4
A63	A64	A62

State Machine
MTR9

Input: ENOUGH
1 = Data insufficient
2 = Data sufficient
3 =
4 =

1	2	3	4
M17	MTR2	NULL	M17
0	A54	0	A107

TABLE D-II (4 of 14)
INTERMEDIATE STATE TRANSITION TABLES

State Machine
MTR10

Input: THRPUT
1 = Sufficient data
2 = No new data
3 = Insufficient data

1	2	3
MTR13	M19	M19
A41	A28	0

State Machine
MTR11

Input: JSTAT - The JTIDS status word managed by the CPC TRJTID.
1 = Threat
2 = Target
3 = Redirect
4 = Urgent Redirect

1	2	3	4
M1	M3	LSTATE	LSTATE
A51	A58	A52	A53

TABLE D-II (5 of 14)
INTERMEDIATE STATE TRANSITION TABLES

State Machine
MTR13

Input: ONPROF <question: 'Does Threat intersect the engaged plan?'>
1 = Not on profile
2 = On profile
3 = Not ready

1	2	3
M21	MTR5	MTR13
A29	A42	A45

State Machine
MTR14

Input: TGPUT - Status index of point insertion
1 = New ID (or new L/L which generated new ID #) .AND. sufficient data
2 = Existing ID, no new data, point on engaged or predicted profile
3 = Undefined
4 = Existing ID, new data, not on a plan
5 = Existing ID, no new data, not on a plan
6 = Insufficient data

1	2	3	4	5	6
M5	M16	0	M5	M27	MTR5
A56	A58	0	A56	A60	A95

TABLE D-II (6 of 14)
INTERMEDIATE STATE TRANSITION TABLES

State Machine
MTR15

Input: PTPATH - Indicator of point type

1 = Non-designated point
2 = Threat
3 = M-GO?
4 = Point on engaged or predicted profile

1	2	3	4
M27	M19	M21	M16
A60	A28	A34	A58

State Machine
MTR18

Input: BLDDAT
1 = TG ID selected, not on engaged or predicted profile.
2 = TG ID not selected
3 = TG ID selected, point on engaged or predicted profile.

1	2	3
M27	M4	M16
A60	0	A58

INTERMEDIATE STATE TRANSITION TABLES

State Machine
MTR20

Input: RDZAT see LOC DD

1	2	3	4	5
M16	M27	M25	M26	M3
A74	A60	A75	A76	0

State Machine
MTR21

Input: COUPIN - Couple pt. status
1 = On engaged plan .and. a small change
2 = On engaged plan but big change .or. off engaged plan

1	2
MTR7	MTR23
A80	A78

TABLE D-II (8 of 14)
INTERMEDIATE STATE TRANSITION TABLES

State Machine
MTR22

INPUTS: RDZSEL
1 =
2 =
3 =
4 =
5 =
6 =
7 =

1	2	3	4	5	6	7
M21	MTR7	M21	MTR7	MTR7	MTR7	M3
A34	A68	A69	A70	A71	A72	0

State Machine
MTR23

Input: GNTSAT < see MTR 5 >

1	2	3	4	5
M3	MTR23	MTR23	M	M
A79	A45	A44	A^{nn}	A^{nn}

TABLE D-II (9 of 14)
INTERMEDIATE STATE TRANSITION TABLES

State Machine
MTR24

Input: ENOUGH
1 = Insufficient
2 = Sufficient
3 = ??????

1	2	3
M25	MTR21	M3
0	A81	A82

TABLE D-II (10 of 14)
INTERMEDIATE STATE TRANSITION TABLES

State Machine
MTR25

Input: COUPEX - Couple pt. existent flag
1 = Exists
2 = Non-existent

1	2
M26	M5
A84	A56

State Machine
MTR26

Input: PTPLAN
1 =
2 =

1	2
M24	M22
A24	A89

TABLE D-II (11 of 14)
INTERMEDIATE STATE TRANSITION TABLES

State Machine
MTR27

Input: NAVSEL
1 = Nothing
2 = Engaged
3 = Predicted
4 = Compute profile
5 = Hold pattern
6 = Pilot relief

1	2	3	4	5	6
M1	M21	M21	MTR7	MTR7	MTR7
0	A34	A94	A95	A97	A96

TABLE D-II (12 of 14)
INTERMEDIATE STATE TRANSITION TABLES

State Machine
MTR28

Input: NAVDAT
1 = Nothing
2 = Stored profile
3 = New plan
4 = Hold pattern
5 = Pilot relief

1	2	3	4	5
M1	M5	M5	M9	M7
0	A98	A99	A100	A101

TABLE D-II (13 of 14)
INTERMEDIATE STATE TRANSITION TABLES

State Machine
MTR30

Input: PLNACT
1 =
2 =
3 =
4 =

1	2	3	4
M21	MTR7	MTR5	M16
A34	A105	A106	0

INTERMEDIATE STATE TRANSITION TABLES

State Machine
MTR31

Input: CPLEAT-
1 =
2 =
3 =
4 =
5 =

1	2	3	4	5
MTR2	M16	M16	M17	M5
A54	A58	A58	A58	0

State Machine
MTR32

Input: XHRDAT-
1 =
2 =

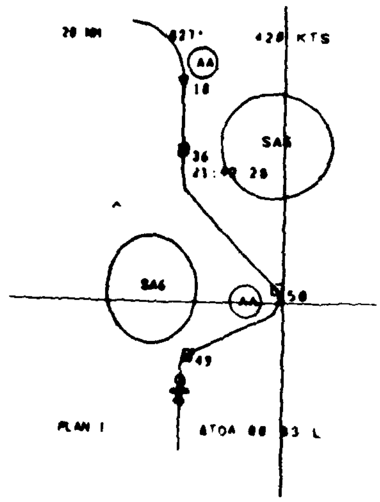
1	2
M21	M27
A34	A60

APPENDIX E

PILOT PRE- AND POST-FLIGHT QUESTIONNAIRES

PRE-FLIGHT QUESTIONNAIRE

INTEGRATED FLIGHT TRAJECTORY CONTROL SYSTEM



FLIGHT DYNAMICS LABORATORY
Air Force Systems Command
Dayton, Ohio

PRE-FLIGHT QUESTIONNAIRE

A. GENERAL

NAME ______________________________

DUTY PHONE ______________ DUTY STATION ______________

CURRENT RESPONSIBILITIES ______________________________

____

____

CURRENT FLIGHT STATUS ______________________________

____

____

SPECIAL TRAINING ______________________________

____

____

____

____

B. SPECIFIC EXPERIENCE

1. HAVE YOU FLOWN AIRCRAFT EQUIPPED WITH A FLIGHT DIRECTOR SYSTEM?

   WHICH AIRCRAFT ______________________________

   ____

   ____

   HOW MANY HOURS ______________________________

   ____

   ____

   HOW DID YOU LIKE IT ______________________________

   ____

   ____

2. HAVE YOU FLOWN AIRCRAFT EQUIPPED WITH A MAP DISPLAY __________

   OR ELECTRONIC HORIZONTAL SITUATION DISPLAY __________?

   WHICH AIRCRAFT ______________________________

   ____

   ____

   HOW MANY HOURS ______________________________

   ____

   ____

   HOW DID YOU LIKE IT ______________________________

   ____

   ____

3. HAVE YOU FLOWN AIRCRAFT EQUIPPED WITH A HEADS UP DISPLAY (HUD) ____?

   WHICH AIRCRAFT ______________________________

   ____

HOW MANY HOURS ____________________

____

HOW DID YOU LIKE IT ____________________

____

4. HAVE YOU FLOWN AIRCRAFT EQUIPPED WITH AN AREA NAVIGATION SYSTEM?

____

WHICH AIRCRAFT ____________________

____

____

HOW MANY HOURS ____________________

____

____

HOW DID YOU LIKE IT ____________________

____

____

5. ARE YOU FAMILIAR WITH THE JOINT TACTICAL INFORMATION DISTRIBUTION SYSTEM (JTIDS) YES ____________ NO ____________

IF YES, HOW WOULD YOU RESPOND TO A JTIDS MESSAGE -

A) ALERTING YOU TO A THREAT.

B) REQUIRING YOU TO DIVERT TO A NEW TARGET.

AD-A084 784 LEAR SIEGLER INC GRAND RAPIDS MICH INSTRUMENT DIV F/G 9/2
FEASIBILITY STUDY FOR INTEGRATED FLIGHT TRAJECTORY CONTROL (FIG--ETC(U)
NOV 79 G L CONEGYS, L ADDIS, J R RING F33615-77-C-3025
UNCLASSIFIED ID-02R-0679 AFFDL-TR-79-3123 NL

4 OF 4
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END
DATE
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6-80
DTIC

C. TIME

1. WHAT ARE THE STEPS YOU GO THROUGH TO PLAN A TACTICAL MISSION AFTER YOU HAVE BEEN TOLD OF YOUR OBJECTIVE?

2. HOW MUCH TIME DO YOU SPEND ON THE GROUND, PLANNING YOUR MISSION?

3. TIME OF ARRIVAL (TOA) IS MORE IMPORTANT (CRITICAL) TO SOME MISSIONS THAN TO OTHERS. HOW LONG IS THE TIME WINDOW (EARLIEST ARRIVAL TIME FOR MISSION SUCCESS MINUS LATEST ARRIVAL TIME FOR MISSION SUCCESS) FOR THE FOLLOWING MISSION TYPES?

   A) AIR TO GROUND WEAPON DELIVERY

   B) RENDEZVOUS

   C) RENDEZVOUS FOR AIR-TO-AIR REFUELING

   D) CLOSE AIR SUPPORT

   E) COMBAT AIR PATROL

4. WHAT IS THE MOST TIME CRITICAL MISSION YOU ARE FAMILIAR WITH ?

A) WHAT ARE THE CONSEQUENCES OF BEING EARLY?

B) WHAT ARE THE CONSEQUENCES OF BEING LATE?

NOTIONS

DO YOU FEEL THAT A ONE MAN CREW CAN HANDLE THE WORKLOAD ASSOCIATED WITH PILOTING A WEAPON DELIVERY AIRCRAFT IN A HOSTILE TACTICAL ENVIRONMENT?

A) DURING VFR OPERATION ____________________

B) DURING NIGHT/ALL WEATHER OPERATION ____________________

HOW WOULD YOU BENEFIT FROM A SYSTEM THAT

A) COULD PROVIDE VERY ACCURATE, UP TO DATE TIME OF ARRIVAL (AT A WAYPOINT OR TARGET) INFORMATION EVEN THOUGH YOU HAVE ENCOUNTERED UNEXPECTED DIFFICULTIES

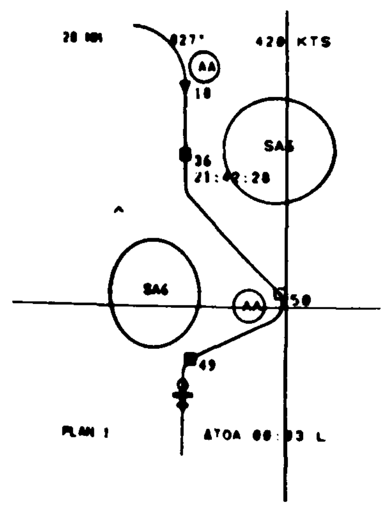
B) COMPUTED AN OPTIMUM THREE DIMENSIONAL FLIGHT PATH AND COMMANDED SPEED FROM YOUR PRESENT POSITION TO A WAYPOINT OR TARGET EVEN THOUGH YOU ARE MAKING EVASIVE MANEUVERS?

A SYSTEM THAT COMPUTES FOUR DIMENSIONAL PROFILES, PROVIDES PROFILE COMMAND INFORMATION AND ACCURATELY PREDICTS TIME OF ARRIVAL (AT A WAYPOINT OR TARGET) IN RESPONSE TO CHANGING THREATS AND EVASIVE MANEUVERS WOULD REDUCE PILOT WORKLOAD IN TACTICAL SITUATIONS.

REQUIRED								UNNECESSARY
EASY								DIFFICULT
CLEAR								CONFUSING
HELP								HINDRANCE
SAFE								DANGEROUS
ACCEPTABLE								UNACCEPTABLE

POST-FLIGHT QUESTIONNAIRE

INTEGRATED FLIGHT TRAJECTORY CONTROL SYSTEM



FLIGHT DYNAMICS LABORATORY
Air Force Systems Command
Dayton, Ohio

POST FLIGHT QUESTIONNAIRE

You have just flown a simulation of a high performance aircraft performing air to ground weapon delivery in a hostile environment. Your simulator aircraft was equipped with an advanced four dimensional navigation and trajectory generation system. We'd like to sample your reactions to the simulation and to the system and we'd like to know how you think we can improve both the simulation and the system. We may not have enough blanks for your answers, so feel free to write on the back of these forms to expand any answers.

NAME: ____________________________________

DATE: ____________________

1. DID YOU FEEL THE SCENARIO PRESENTED WAS REALISTIC OF THOSE PROJECTED BY OPERATIONAL COMMANDS? WHAT WOULD MAKE IT MORE REALISTIC?

2. WHAT DID YOU NOTICE MOST DURING THE FLIGHT?

3. WHICH DO YOU CONSIDER MOST IMPORTANT (CHECK ONE):

- ☐ MISSION ACCURACY
- ☐ REDUCED WORKLOAD
- ☐ OTHER (SPECIFY)

4. WHAT DID YOU USE AS A JUDGE OF PERFORMANCE OF THE SYSTEM?

5. WHEN DID YOU FEEL COMFORTABLE WITH THE USE OF THE SYSTEM?

6. GIVE YOUR ESTIMATE OF ADDITIONAL TRAINING TIME THAT WOULD BE REQUIRED IF THIS SYSTEM WERE IMPLEMENTED IN A FIGHTER.

____

____

____

____

7. WHAT OPERATIONAL NEEDS DO YOU THINK A TRAJECTORY GENERATOR WILL SATISFY?

____

____

____

8. THE IFTC SYSTEM THAT COMPUTES FOUR DIMENSIONAL PROFILES, PROVIDES PROFILE COMMAND AND ACCURATELY PREDICTS TIME OF ARRIVAL (AT A WAYPOINT OR TARGET) IN RESPONSE TO CHANGING THREATS AND EVASIVE MANEUVERS WOULD REDUCE PILOT WORK-LOAD IN TACTICAL SITUATIONS.

REQUIRED								UNNECESSARY
EASY								DIFFICULT
CLEAR								CONFUSING
HELP								HINDRANCE
SAFE								DANGEROUS
ACCEPTABLE								UNACCEPTABLE

9. DO YOU FEEL THAT A ONE MAN CREW CAN HANDLE THE TACTICAL ENVIRONMENT WORK-LOAD? ______________ EXPLAIN (I.E., WITH AUTOPILOT)

____

____

10. DO YOU FEEL THAT THE 4D IFTC SYSTEM WOULD IMPROVE MISSION TIME OF ARRIVAL ACCURACY?

significant improvement						no improvement

11. DO YOU FEEL THAT THE 4D IFTC SYSTEM WOULD REDUCE MISSION PLANNING TIME?

significant reduction						significant increase

EXPLAIN:

12. DO YOU FEEL THAT THE THREAT AVOIDANCE FEATURE IS BENEFICIAL?

significant benefit						no benefit

EXPLAIN:

13. DO YOU FEEL THAT THE CAPTURE PROFILE FEATURE IS BENEFICIAL?

significant benefit						no benefit

14. WHAT IS YOUR REACTION TO THE PROGRAMMED INTERACTION BETWEEN THE MODE SELECTION, THE STATUS DISPLAY AND MAP DISPLAY?

15. WOULD THIS FEATURE (THE PROGRAMMED INTERACTION) REDUCE PILOT WORKLOAD?

significant reduction						no reduction

16. RATE DIFFICULTY OF THE FOLLOWING:

A. BUILDING AND INSERTING THE FLIGHT PLAN

simple						impossible

B. CHANGING THE FLIGHT PLAN

simple						impossible

C. OBTAINING PRESENT POSITION INFORMATION

simple						impossible

D. DECIPHERING DATA LINK INFORMATION

simple						impossible

17. WAS THE INFORMATION SUPPLIED BY THE SPECIAL DATA PAGES INSUFFICIENT, SUFFICIENT OR EXCESSIVE?

WHAT INFORMATION WAS MISSING? ______________________

WHAT INFORMATION WAS EXCESSIVE? ______________________________

18. RATE THE DESIRABILITY OF THE FLIGHT DIRECTOR COMMANDS.

19. WHAT FUNCTIONS DO YOU FEEL NEED TO BE COUPLED WITH THE AUTOPILOT?

20. WERE THE ALTITUDE COMMANDS SUFFICIENT?

21. HOW READABLE WAS THE CRT MAP DISPLAY?

22. DO YOU FEEL THAT A PROJECTED MAP DISPLAY WOULD BE BENEFICIAL?

significant benefit						no benefit

23. WHAT IS YOUR FEELING ON A MAP DISPLAY?

required						not required

24. DO YOU FEEL THAT A HUD IS NEEDED/REQUIRED?

required						not required

EXPLAIN:

____

____

____

25. WHAT IMPROVEMENT/CHANGES WOULD YOU LIKE TO SEE?

____

____

____

26. WHAT WOULD YOU LIKE TO RETAIN (WITH OR WITHOUT MODIFICATIONS)?

____

____

____

27. WOULD ANY ADDITIONAL DISPLAYS BE USEFUL?

28. WOULD YOU LIKE TO REARRANGE THE INSTRUMENT PANEL LAYOUT?

29. DO YOU FEEL THAT THE INFORMATION PRESENTED ON THE VSD MODE IS BENEFICIAL?

significant benefit						not required

30. WHEN IS THE VSD MOST USEFUL?

31. DO YOU HAVE A DESIRED FORMAT FOR THE VSD?

*U.S.Government Printing Office: 1980 — 657-084/422