

To the Graduate Council:

I am submitting herewith a thesis written by John William Scanlan II entitled "A Qualitative Assessment Of A Passive Low Altitude Terrain Following System For Tactical Bombers As Modeled On The Tornado Aircraft." I have examined the final copy of this dissertation for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Master of Science, with a major in Aviation Systems.

Ralph D. Kimberlin
Ralph D. Kimberlin, Major Professor

We have read this thesis
and recommend its acceptance:

G. Peter Solies
Fred Watts

Accepted for the Council:

C. W. Mink
Vice Provost
and Dean of The Graduate School

STATEMENT OF PERMISSION TO USE

In presenting this thesis in partial fulfillment of the requirements for a Master's degree at The University of Tennessee, Knoxville, I agree that the Library shall make it available to borrowers under rules of the Library. Brief quotations from this thesis are allowable without special permission, provided that accurate acknowledgement of the source is made.

Requests for permission for extensive quotations from or reproduction of this thesis in whole or in parts may be granted by the copyright holder.

Signature John William Scala

Date 15 July 1990

A Qualitative Assessment
Of A Passive Low Altitude Terrain Following System
For Tactical Bombers
As Modeled On The Tornado Aircraft

A Thesis
Presented for the
Master of Science
Degree
The University of Tennessee, Knoxville

John William Scanlan II
August 1990

DEDICATION

To Amy, my wife, friend, and companion, who has encouraged and supported me throughout my education and our life. To Shannon, my daughter, who understood when I was locked in my office for evenings on end, and to my new buddy, John Michael.

ACKNOWLEDGEMENTS

The author would like to extend his thanks to everyone who helped make this paper a reality. In particular, I am indebted to Professor Ralph D. Kimberlin, Dr. U. Peter Solies and Professor C. Fred Watts, who served as my director and committee, respectively. For their time and effort explaining and demonstrating the Tornado to me, a special thanks to Comandante Carlo Revetria, the men and officers of 311^o Gruppo Volo, the Italian Test Directorate and Major Martin Arzenberger from the Military Aircraft Division, Messerschmitt-Bolkow-Blohm.

I also wish to thank Mr. Robert Redditt, a fine engineer and good friend, for his countless hours assisting me with computer programming and simulation. Additional thanks to Kathryn "Kap" Vincze, for her hours and care ensuring that the newly established extension campus at China Lake California survived to allow other students to pursue their master's degrees. Appreciation is also extended to Dr. Borjn for his time and patience.

Foremost, I am forever grateful to my wife, Amy, for her professionalism as a technical writer and editor, and for her constant "sanity checks" throughout the writing of this paper.

I hereby acknowledge, with thanks, the permission granted by Rockwell International, to use figures and diagrams from the Global Positioning System A Compilation Of Papers, Book Two (1988).

ABSTRACT

Although combat aircraft designers face similar design conflicts as their commercial and civil aerospace contemporaries, they also experience the additional challenge of designing a vehicle that is survivable in the combat environment. The military user defines the expected threat environment for the vehicle. Based on this characterization, the designer incorporates survivability characteristics to reduce the aircraft's susceptibility and vulnerability. The lengthy design, prototype, test, and production process leaves the new aircraft exposed to new or improved threats fielded during that time. This evolving threat necessitates a continuous cycle of modifications and improvements throughout the vehicle's life to ensure that the aircraft remains effective and survivable.

The Tornado GR Mk1 Multi-Role Combat Airplane is a twin engine, fighter-bomber representative of high speed, low altitude, all weather aircraft designed to penetrate enemy defenses using sophisticated avionics and terrain following capabilities. Other examples of this class include the U. S Navy's A-6 and the Air Force's B-52, F-117, B-1, and B-2 aircraft. The low altitude radar penetration systems, while extremely capable, can be vulnerable to jamming, deception, and adverse weather. Additionally, the use of terrain following radar can increase an aircraft's susceptibility by hostile Electronic Support Measures (ESM) systems and increases its susceptibility to integrated air defense systems. The employment of highly accurate position and velocity data from the NAVSTAR Global Positioning System (GPS), together with the Digital Terrain Elevation Data (DTED)

could provide a beneficial navigation and survivability enhancement design for use by this type of aircraft.

The objectives of this thesis are: (1) to propose a model of an alternate passive navigation and terrain following capability that could be easily incorporated into the Tornado and other aircraft in its category, (2) to evaluate the error contributions of components of the proposed penetration system and quantify the possible low altitude flight capabilities of an aircraft using the system, (3) qualitatively assess the technical, operational, and economical feasibility of the system and (4) evaluate potential susceptibility and survivability benefits of the system.

These goals will be achieved by researching the technical and operational flight test data for the components of the passive penetration system and combining that information with flight test information collected during an assessment of the Tornado aircraft (USNTPS DT-II). Quantitative assessments of the capability of the proposed system will be based on analysis of literature specifications augmented by flight test results when available. A simple model of the penetration system, showing the required data inputs and control outputs, will be used to examine the potential incorporation methodology and the technical mechanization. Finally, use of a simplified scenario in a survivability model will provide an assessment of the capability and potential survivability improvements from retrofitting the passive system in the Tornado aircraft.

PREFACE

" The survival of a military aircraft operating in a hostile environment depends upon many diverse factors, such as the design of the aircraft, the skill and experience of the crew, the armament carried, the onboard countermeasures equipment, the offboard supporting systems, and the tactics employed. The cost of modern aircraft weapon systems, coupled with the requirement that the system be *effective*, makes imperative the consideration of the aircraft's survivability throughout the life cycle of the system."

Anonymous

TABLE OF CONTENTS

SECTION		PAGE
1	INTRODUCTION.....	1
2	BACKGROUND	4
	Threat Definition.....	4
	Threat Engagement Sequence.....	5
	Terrain Following Flight Design Philosophies	7
3	TORNADO AIRCRAFT DESCRIPTION.....	10
	General Aircraft Characteristics	10
	Tornado Integrated Navigation and Attack System.....	11
	Terrain Following System Overview	13
	Main Computer.....	15
	General.....	15
	Main Computer Components.....	16
	Interface Units.....	16
	Operational Flight Program	17
	Computer Operation	18
	Inertial Navigator	20
	General.....	20
	Components.....	23
	Inertial Navigator Unit	23
	Inertial Navigator Control and Display Unit	23
	IN Operation.....	23
	Secondary Attitude and Heading Reference	25
	Gyro and Electronics Unit.	26
	Magnetic Detector Unit.	26
	Control and Remote Compensator Unit.....	26
	SAHR Operation.....	26
	Air Data Computer	27

TABLE OF CONTENTS (Continued)

SECTION		PAGE
3	Terrain Following Radar.....	28
	Terrain Following Radar Components.....	28
	Transmitter.....	28
	Antenna/Receiver.....	28
	Radar Mount/Roll Unit.	29
	Processor/Computer.	29
	Terrain Following System Operation	29
	Pulse Generation.....	30
	Terrain Elevation Measurements.....	31
	Terrain Following Flight Procedures.....	33
4	PROPOSED PASSIVE SYSTEM	38
	Introduction	38
	Statement of Need.....	45
	Requirements Definition	48
	Integration Concept.....	49
	Digital Terrain Elevation Data	51
	Global Positioning System Overview	56
	Fundamentals of Ranging.....	58
	GPS Satellite Operation.....	63
	GPS User Equipment Operation	66
	GPS System Performance Characteristics.....	67
	Description of Errors.....	70
5	SYSTEM CONFIGURATION	74
	Integration Options	74
	P ³ S Hardware-to-Aircraft Interfaces	80
	P ³ S Component Placement.....	82
	Interface Requirements	84
	P ³ S Implementation Costs.....	86

TABLE OF CONTENTS (Continued)

SECTION		PAGE
5	P ³ S Concept of Operations	87
6	PASSIVE TERRAIN FOLLOWING SYSTEM SIMULATION AND EVALUATION	96
	Simulation Plan and Philosophy	96
	Simulation Description	97
	Simulation Analysis	101
7	CONCLUSIONS AND RECOMMENDATIONS	105
	Conclusions	105
	Recommendations	108
	LIST OF REFERENCES	109
	APPENDICES	113
	APPENDIX A	114
	APPENDIX B	132
	APPENDIX C	136
	VITA	152

LIST OF TABLES

TABLE		PAGE
3-1	Standard Discretes	17
3-2	Inertial Navigator Operating Limits.....	20
3-3	Inertial Navigation Alignment Times	24
3-4	Ride Settings and g-Command Schedule	32
4-1	Tornado Test Configurations	39
4-2	Attribute Ranking From Aviator Questionnaire.....	41
4-3	Normalized Attribute Weights	42
4-4	Calculation of Weighted Scores and Alternative Rankings	43
4-5	Radar Terrain Following Characteristics.....	49
4-6	Specified Digital Terrain Data Accuracies.....	52
4-7	Typical DTED Accuracy Ranges.....	52
4-8	GPS Characteristics	57
4-9	C/A and P Code Characteristics	63
4-10	GPS System Accuracy Specifications	68
4-11	GPS System Error Budget.....	70
4-12	Figure of Merit Values.....	73
5-1	Comparison of Direct Versus Cascading Integration Strategies.....	77
5-2	Major Cost Contributors for P ³ S Implementation.....	87
6-1	Impact Summary of 864 Simulation Runs	102
6-2	Impact Versus Terrain Following Altitude for Terrain Segment One.....	103

Appendix B

B-1	Tornado Operational Characteristics and Dimensions.....	131
B-2	Main Computer Performance Characteristics	132
B-3	GPS Control Segments Locations and Functions	133
B-4	GPS User Equipment Specifications.....	134

LIST OF FIGURES

FIGURE		PAGE
2.1	Threat Engagement Envelop.....	6
2.2	Integrated Air Defense System with Threat Overlap and Layering...	7
2.3	Calculation of Critical Points to Generate Climb Commands.....	8
3.1	Functional Block Diagram of Tornado Weapon System	12
3.2	Combined Radar and Projected Map Display (CRPMD).....	14
3.3	Operational Flight Program Task Computer Iteration Rates.....	19
3.4	Inertial Navigator Functional Block Diagram.....	22
3.5	Zero Command Line Dynamic Variations.....	35
3.6	Terrain Following Command Generation	36
4.1	Steps of the GPS System Integration Process.....	44
4.2	Sample Digital Terrain Data.....	54
4.3	Vertical Obstruction Types and Uncertainties.....	55
4.4	Single Satellite Position Ambiguity.....	60
4.5	GPS Range Uncertainty	61
4.6	Two Dimensional Example of Satellite-to-User Range Ambiguity Due To Clock Error.....	62
4.7	GPS Navigation Solution	62
4.8	GPS Satellite Signal Modulation Techniques Combining Signals For Transmission.....	64
4.9	Spread Spectrum Signal Processing	65
4.10	Generic Receiver Operation	66
4.11	Types of Geometric Dilution of Precision	69
5.1	Diagram of Proposed Fully Integrated GPS UE	75
5.2	Cascading Closed-Loop GPS/INS Aided Configuration	78
5.3	GPS UE System Architecture.....	80
5.4	Proposed Location of P ³ S System Components.....	82
5.5	Simplified AC Power Distribution for P ³ S Components.....	84
5.6	Sample Terrain Masking Calculation Made by Mission Planning System	88
5.7	Sample Radar Terrain Masking Plot of a Typical Radar Site.....	89
5.8	Functional Diagram of Proposed Software Modules for the P ³ S.....	91
5.9	P ³ S Flight Path Generation	95
6.1	Input Page for P ³ S Simulation.....	97
6.2	Terrain Interpolation and Horizontal Position Errors.....	99
6.3	Sample P ³ S Simulation Runs Depicting Terrain Following Flight Path and Aircraft Impacts.....	101

LIST OF FIGURES (Continued)

FIGURE		PAGE
Appendix A		
A-1	Cutaway View of Tornado Aircraft.....	113
A-2	3-Dimensional View of the Tornado Aircraft.....	114
A-3	View of Tornado Aircraft's Aft Cockpit of	115
A-4	Diagram of Tornado Flight Controls	116
A-5	Mission Computer Format	117
A-6	Inertial Navigator Inputs and Outputs	118
A-7	Navigation System Flow Diagram for the Doppler and SAHR Mode.....	119
A-8	Terrain Following Radar Component Locations.....	120
A-9	TFR Vertical Steering Commands and Displays	121
A-10	TFR Pitch Command Generation.....	122
A-11	Terrain Following Radar System Block Diagram	123
A-12	Terrain Following Route One.....	124
A-13	Terrain Following Route Two.....	125
A-14	GPS Sample Data Message Format.....	126
A-15	Collins GPS User Equipment Diagram	127
A-16	Cassette Preparation Ground Station.....	128
A-17	Proposed Planning System Architecture	129
A-18	Terrain Perspective From Modeling Digital Terrain.....	130

ABBREVIATIONS

AAA	Anti-Aircraft Artillery
ADC	Air Data Computer
AFDS	Autopilot Flight Director System
AFP	Automatic Flight Program
AI	Airborne Interceptor
BIT	Built In Test
BITE	Built In Test
C	Centigrade
C/A	Coarse Acquisition
CAS	Calibrated Airspeed
CD	Compact Disk
CEP	Circular Error Probable
CRPMD	Combined Radar and Map Display
CSAS	Command and Stability Augmentation Unit
CVR	Cockpit Voice Recorder
db	Decibels
DMA	Defense Mapping Agency
DFP	Desired Flight Path
DoD	Department of Defense
DOF	Degree Of Freedom
DSC	Digital Scan Converter
DTED	Digital Terrain Elevation Data
E	East
ECEF	Earth Centered Earth Fixed
ELINT	Electronic Intelligence
EPROM	Erasable Programmable Read Only Memory
ESM	Electronic Support Measures
FLIR	Forward Looking Infrared Radar
ft	Feet
FOM	Figure Of Merit
g	Acceleration
GDOP	Geometric Dilution Of Precision
GHz	Gigahertz
GMR	Ground Map Radar
GPS	Global Positioning System
HDOP	Horizontal Dilution Of Precision
HOW	Handover Word
HSI	Horizontal Steering Indicator
HUD	Head-Up Display
Hz	Hertz
IADS	Integrated Air Defense System

ABBREVIATIONS (Continued)

IF	Intermediate Frequency
IFU	Interface Unit
IN	Inertial Navigator
INCDU	Inertial Navigator Control and Display Unit
INS	Inertial Navigation System
IMN	Indicated Mach Number
KF	Kalman Filter
km	Kilometers
LAN	Local Area Network
lb	Pounds
LPI	Low Probability of Intercept
MFP	Manual Flight Program
MC	Main Computer
MFK	Multi-Function Keyboard
MHz	Megahertz
min	Minute
mm	Millimeter
MSL	Mean Sea Level
N	North
NM	Nautical Mile
OFF	Operational Flight Program
P	Precise
P ³ S	Proposed Passive Penetration System
P/C	Processor/Computer
PDOP	Position Dilution Of Precision
PN	Pseudorandom Noise
pps	Pulses per Second
PPS	Precise Positioning System
PSU	Program Storage Unit
R	Range
RAM	Random Access Memory
RF	Radio Frequency
RP	Receiver Processor
S	South
SAHR	Secondary Attitude and Heading Reference
SAM	Surface-To-Air Missile
SPS	Standard Positioning Service
SV	Satellite Vehicle
TA	Terrain Avoidance
TAS	True Airspeed
TDOP	Time Dilution Of Precision

ABBREVIATIONS (Continued)

TERCOM	Terrain Contour Matching
TF	Terrain Following
TFR	Terrain Following Radar
TNR	Tornado Nose Radar
TV/TAB	Television/Tabula
UERE	User Equivalent Range Error
UE	User Equipment
VOD	Vertical Obstruction Data
W	West
x,y,z	Pitch, Roll and Yaw Orthogonal axis
ZCL	Zero Command Line

1. INTRODUCTION

Analysis of recent combat aircraft losses demonstrates that an aircraft must be designed to survive in its operational threat environment or it will be unable to accomplish the mission for which it was built [1 Ball]. Studies also reveal that as threat system's effectiveness has increased, aircraft required to operate in sophisticated threat environments have become less effective and survivable. Because of the protracted design, prototype, test and production process, recently fielded aircraft face new and improved threat capabilities [2 Solies]. To counter this trend, aircraft designers must continually evaluate potential survivability enhancement features for integration throughout the platform's life cycle. However, retrofitting these survivability enhancement features into existing aircraft can often result in reduced performance capabilities and effectiveness. Examples of some retrofitting penalties include reduced combat ranges, degraded maneuverability, unsatisfactory flying and handling qualities, or increased aircrew workloads. To prevent this reduced aircraft effectiveness, the designer must use sound analysis to investigate each potential enhancement feature and incorporate it only if there are no excessive penalties. This trade-off study must review each design enhancement and assess its impact in areas such as aircraft effectiveness, safety, cost, performance, weight, reliability, and maintenance. In addition, the synergistic benefits from the enhancement must be examined

- other than improved survivability, what additional advantages or effectiveness increases could be gained if the change were incorporated?

In November 1986, flight tests on the Panavia Tornado aircraft indicated a capable, effective airplane representative of many modern fighter-bombers including the Navy's A-6 and the Air Force's B-52, F-117, B-1 and B-2 aircraft [3 Scanlan]. These aircraft have been designed for and routinely fly at high speeds and low altitudes to penetrate sophisticated enemy early warning networks and minimize their exposure to enemy air defenses. Most of the above aircraft have some form of a Terrain Avoidance (TA) or Terrain Following (TF) system that uses active radar Radio Frequency (RF) emissions to scan the terrain along the aircraft's flight path. For example, the Tornado's dedicated Terrain Following Radar (TFR) uses continuous Ku band radar emissions to detect and measure the range and altitude of the terrain ahead of the aircraft. The TFR, although extremely effective, can be vulnerable to failure, jamming, deception, or degradation in adverse weather. Most importantly, the very system that permits the aircraft to fly at low altitudes to prevent detection also acts as a beacon to hostile Electronic Support Measure (ESM) and Electronic Intelligence (ELINT) systems. The emissions from a terrain following radar can be detected from hundreds of miles, increasing the aircraft's susceptibility to enemy Integrated Air Defense Systems (IADS).

This thesis proposes an alternative, complimentary TF system that would use positioning data from the NAVSTAR Global Positioning System (GPS) with digital map data to permit passive (non-emitting) terrain following flight. The existing Tornado TFR system definition is followed by an in-depth description of the major components of the proposed passive

system. The integration and operation of the proposed system, as well as the position errors in each component, are presented. Estimates of the system's low altitude flight capabilities are made based on a simple computer model. Potential susceptibility and survivability benefits of the proposed system are also examined. Finally, in the austere defense climate of the 1990s, no proposed enhancement escapes stringent financial scrutiny; therefore, an estimate of the cost of the proposed system hardware is made and potential synergistic benefits are reviewed.

2. BACKGROUND

Threat Definition

An aircraft designer's ability to understand, design, and evaluate survivability enhancement features is predicated on a thorough understanding of the threats that aircraft will face. The aircraft designer must work with intelligence agencies and threat analysts to ensure all existing threats are correctly identified and future threats have been accurately forecast.

All threats to be considered in a survivability enhancement analysis can be divided into four categories. The most common and diverse threat is the gun, defined as a device using explosive charges to fire a projectile. Guns exist in all sizes and calibers from hand-held personal weapons to large, stationary Anti-Aircraft Artillery (AAA). The second category includes the Surface-to-Air Missile (SAM), which is normally more complex than the gun system and employs various tracking and guidance systems to direct a missile to an intercept point with the target aircraft. Like the gun, the SAM threat can be hand-held, employing a simple optical guidance system, or can be a fixed complex of acquisition and guidance radars, computers, and missile transport/launchers. The third threat category is the Airborne Interceptor (AI). This enemy aircraft's primary mission is to locate, track, and destroy airborne targets using various airborne guns and missiles. Similar to the gun and the SAM, the AI can operate autonomously or as part of an integrated system. The AI, however,

differs from the gun or the SAM since it is highly mobile and can rapidly change search and engagement areas. This mobility makes the AI the most difficult threat for survivability enhancement proposals that rely on avoidance of known threat locations to reduce threat exposure. A directed energy device is the newest and final threat category. This device produces a beam of high energy electromagnetic radiation in the form of particles or waves travelling at the speed of light. The beam is capable of blinding sensors and aircrew or inflicting damage on the target. Current directed energy weapons require large amounts of electrical power to generate their destructive beams. For this reason, most current generation directed energy weapon prototypes and fielded units are large and semi-permanent sites. Unfortunately, rapid scientific advancements in this technological field will reduce the size and improve the capabilities of this class of weapon, making it a critical threat for designers of current generation aircraft survivability enhancements.

Threat Engagement Sequence

To successfully engage a target, each threat category must complete a similar engagement sequence of detecting, identifying, tracking, and firing or launching on a target. Sufficient information must be available for the threat to accurately determine the target aircraft's heading, speed, range, elevation, and azimuth. A threat's operational capabilities determine its ability to gather this required information and to engage a target. Some of these capabilities are initial reaction time, maximum detection ranges, acquisition time, tracking rates, launch and intercept

envelopes, rate of fire, and firing doctrine. Figure 2.1 depicts a typical threat system and some limits imposed by its operational capabilities.

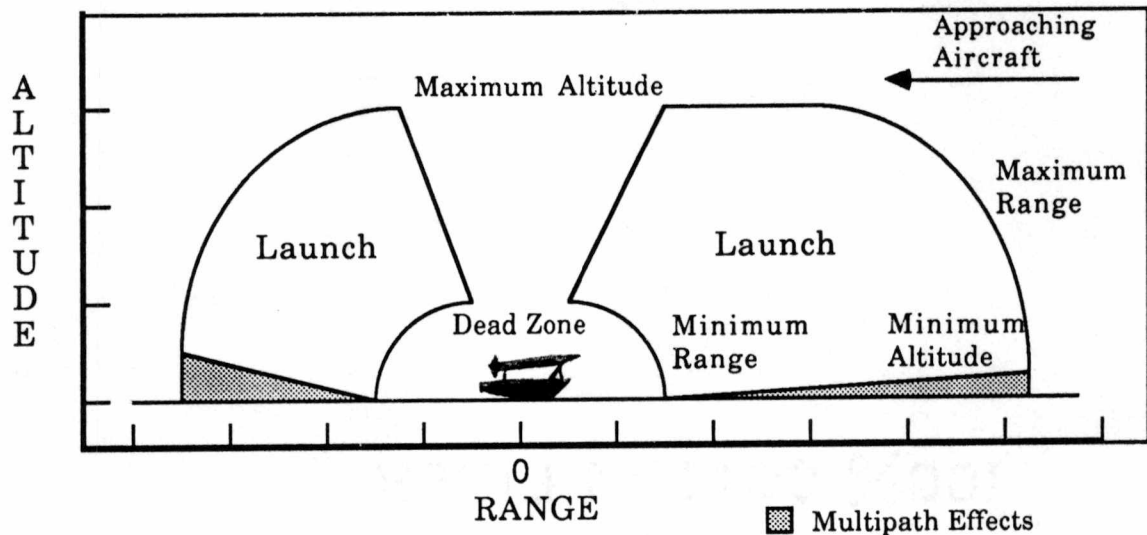


Figure 2.1. Threat Engagement Envelop

Combat doctrine often compensates for individual system operational capability limitations by increasing the threat density or by linking dissimilar threats to form an overlapping, IADS. Multiple acquisition systems, including passive ESM and ELINT systems and elevated radars are employed to achieve maximum detection and warning. Figure 2.2 presents an example of a typical integrated threat the Tornado might face. Flight tests were conducted to evaluate the performance of the Tornado against a sophisticated air defense threat.

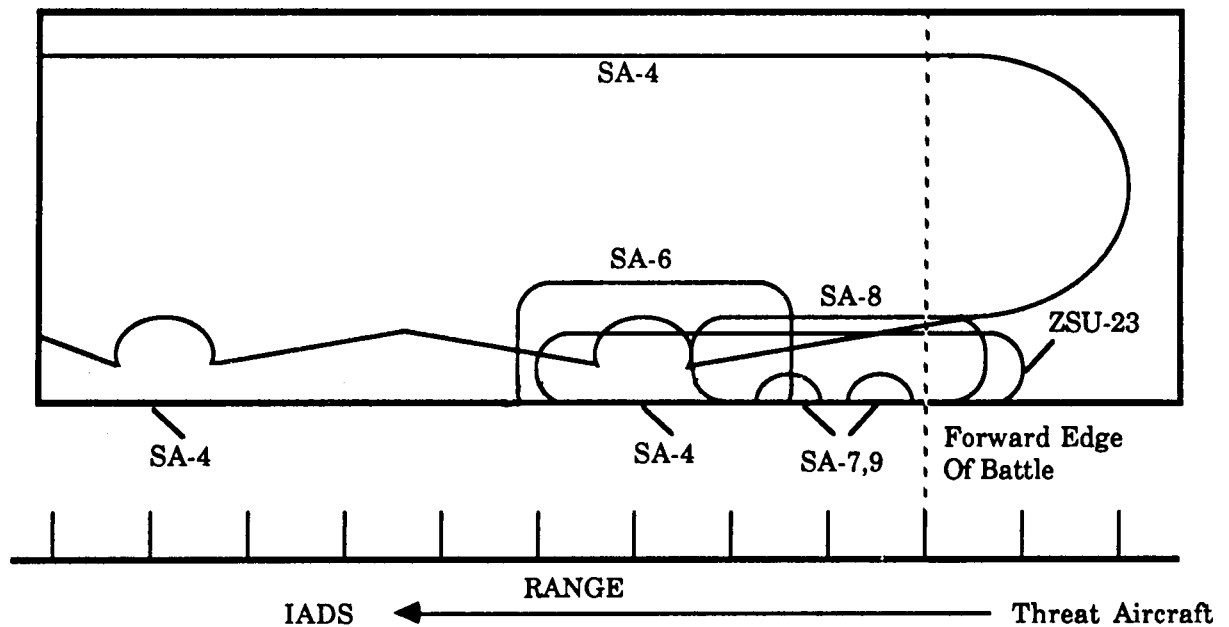


Figure 2.2. Integrated Air Defense System with Threat Overlap and Layering

Terrain Following Flight Design Philosophies

Early anti-air systems, designed for high speed, high altitude targets had limited capabilities against low altitude aircraft. To counter these threat systems, the United States and NATO tactical and strategic doctrine was developed, promoting the use of low level penetration tactics to degrade the capabilities of known threats [4 Baird]. This doctrine postulated low altitude terrain following flight to minimize exposure time, thereby reducing threat detection, acquisition, and tracking times; shrink engagement envelopes; and disrupt firing doctrines.

Traditional terrain following aircraft designs involved the use of constantly radiated Radio Frequency (RF) emissions to generate a picture of the terrain in front of the aircraft. At a series of critical points, the TF

system would generate vertical commands required to sustain a set flight clearance height over the terrain, as illustrated in Figure 2.3. Calculation of acceleration commands continues as the aircraft progresses along it's planned flight path.

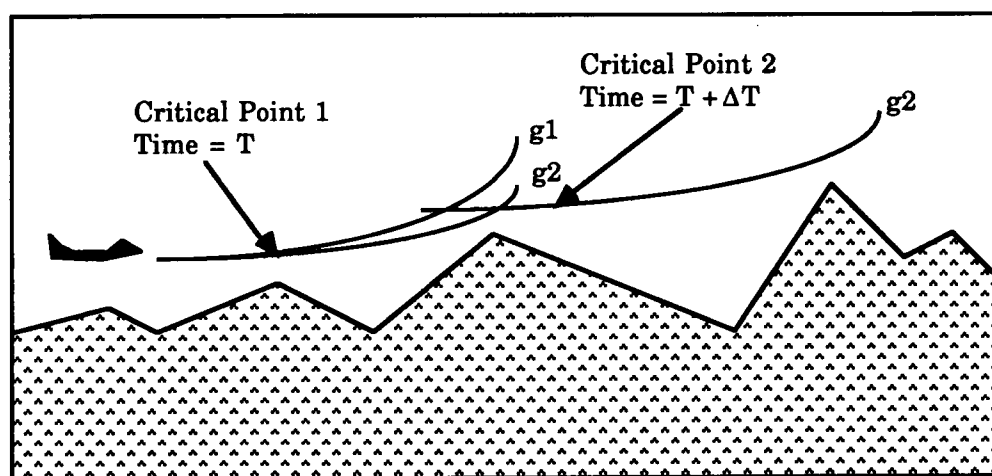


Figure 2.3. Calculation of Critical Points to Generate Climb Commands

This "up and over" design approach was mandated by the state of flight control and avionics development. Lateral threat avoidance was accomplished by preflight planning. A penetration route was planned which avoided known threat locations by using straight segments connected with planned standard rate turns [5 Christensen]. When faced with "climb or turn" decisions, the automatic TF system would execute the vertical command first.

Since the origin of the low altitude doctrine and the introduction of the Tornado in the early 1970s, the air defense threat has also continued to evolve. The sophistication and capabilities of many of the new weapons and their integration into defensive networks poses an unacceptable threat to current generation aircraft [6 Huss]. This threat is one the Tornado faces

when attempting to penetrate current Soviet and Warsaw Pact air defense systems. The traditional decoupled design of the Tornado, with its separate vertical and horizontal channels, permits limited horizontal maneuvering based on the TFR capabilities.

3. TORNADO AIRCRAFT DESCRIPTION

General Aircraft Characteristics

To serve as a baseline for the proposed passive penetration system a complete description of the Tornado is presented. A detailed discussion of its terrain following system components, integration, and operation are provided to clarify the proposed system's feasibility and compatibility.

The Tornado GR Mk 1 Multi-Role Combat Airplane (Appendix A, Figures 1 and 2) is a twin-engined, supersonic, variable geometry sweep-wing fighter-bomber with an empty gross weight of 45,000 pounds (lb) and a maximum operating weight of 60,000 lb. Three versions of the Tornado are operated by the air forces and navies of the three European countries. Manufactured by Panavia Aircraft ⁽¹⁾, the tandem seat Tornado is flown by a crew of two, a pilot in the forward cockpit and a navigator/weapon operator in the aft cockpit (Appendix A, Figure 3). The airplane is powered by two Turbo-Union RB 199-34R Mk-103, three spool, turbofan afterburning engines enabling the aircraft to reach airspeeds in excess of 1.1 Indicated Mach Number (IMN) in the low altitude regime.

The aircraft flight system is a triplex "fly-by-wire" Command and Stability Augmentation System (CSAS) which processes the pilot's manual

(1) Panavia Aircraft was formed on 26 March 1969 to design, develop and produce an all-weather attack aircraft for the air forces of the Federal Republic of Germany, the United Kingdom and Italy, and the navy of the Federal Republic of Germany.

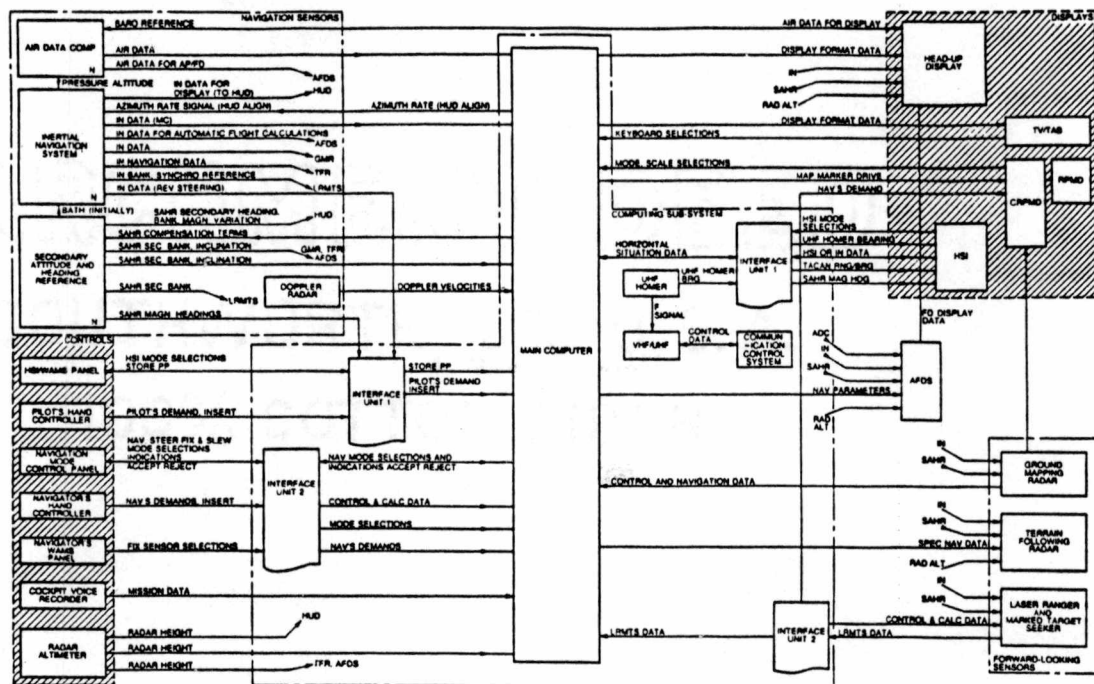
inputs and autopilot commands into stabilized electrical commands. The flight controls depicted in Appendix A, Figure 4, include the all-moving tailplane halves (tailerons), rudder, and upper surface spoilers with additional flight control supplied by the hydraulically powered wing sweep, flaps, slats, Krueger flaps, and speedbrakes.

The Tornado's combat package includes a wide variety of air-to-air and air-to-surface ordnance. The Tornado is fitted with twin 27 millimeter (mm) IWKA Mauser cannons and can carry Sidewinder, HARM, and ALARM missiles for self-protection. All aircraft weapons are carried externally on swiveling, underwing pylons designed to counteract the wing sweep at high IMN by remaining aligned with the fuselage datum line. (Tornado operational dimensions and weights are presented in Appendix B, Figure 1. A detailed description of the Tornado GR Mk 1 airplane is presented in the Tornado Aircrew manuals, References 7, 8, and 9.)

Tornado Integrated Navigation and Attack System

The Tornado Integrated Navigation and Attack System is composed of a suite of active and passive sensors, data processing computer and cockpit displays and controls, all integrated to enable the airplane to fly high speed, low altitude, all weather, terrain following navigation. The three primary functional groups - Sensors, Data Processing, and Displays - are combined with three secondary functional groups to form the Tornado's avionics suite. The secondary functional groups are the Armament, Electronic Support Measures, and Communication and Identification systems. The avionics suite is designed to allow the aircrew to locate and

destroy defended ground or maritime targets. A simplified block diagram of the Tornado weapon system is presented in Figure 3.1. While essential to the overall mission effectiveness, the systems of the secondary functional groups do not contribute to the TF capabilities of the aircraft and are not detailed in this paper.



AFDS: Autopilot and Flight Director System
 LRMTS: Laser and Marked Target Seeker
 TV/TAB: Television/Tabular Display
 SAHR: Secondary Attitude and Heading Reference
 WAMS: Weapon Aiming Mode Selectors
 RPMD: Repeater Projected Map Display
 CRPMD: Combined Radar Projected Map Display

HUD: Head Up Display
 GMR: Ground Mapping Radar
 IN: Inertial Navigator
 HSI: Horizontal Situation Indicator
 TFR: Terrain Following Radar
 ADC: Air Data Computer

Figure 3.1. Functional Block Diagram of Tornado Weapon System

Aircraft positioning and navigation data is provided by a Ferranti FIN 1010 three axis digital Inertial Navigation System (INS) and a Decc Type 72 doppler radar system. Air mass and altitude information are supplied by a Microtecnica Air Data Computer (ADC) and an Aeritalia radar altimeter. Avionics control and computer processing are provided by the Litef LR-1432 micro-programmed, general purpose digital computer. The MIL-STD-1553 compatible computer acts as a bus controller or a remote terminal. The high speed computer processes data from the sensors to display navigation steering or weapon aiming information to the crew. Other sensor data is processed and provided to the Autopilot Flight Director System (AFDS) for automatic route and terrain following capability.

Terrain Following System Overview

The primary components of the Tornado terrain following system are the all weather Tornado Nose Radar (TNR), the computer, and the navigation system. The radar consists of two separate systems- the Terrain Following Radar (TFR) and the Ground Mapping Radar (GMR) - which share a common mounting, power supply, and computer/processor. The GMR is the primary attack sensor for navigation updating, target identification and fire control. The GMR operates in the Ku (J) frequency band and has nine operating Modes: Readiness Test, Ground Mapping, Height Finding, Air-to-Ground Ranging, Air-to-Air Tracking, Land/Sea Target Lock-on, Home-On-Jam, and Beacon Homing. The GMR operates independently of the TFR and is used to update the Doppler-monitored, INS.

Three of six GMR components, the Processor/Computer, the Radar Mount/Roll Unit, and the Power Supply, are shared by the GMR and the TFR. The GMR system performs a number of functions including ground mapping, contour mapping on boresight, target height finding, air-to-ground ranging, A/A tracking, Home-on-Jam and beacon. The GMR is designed to make use of extensive electronic counter-counter measures to enhance operational effectiveness in electronic jamming environments. Ground map video is displayed on the Combined Radar and Projected Map Display (CRPMD), Figure 3-2, which also provides operational mode controls to manage the radar and map video is displayed on the screen.

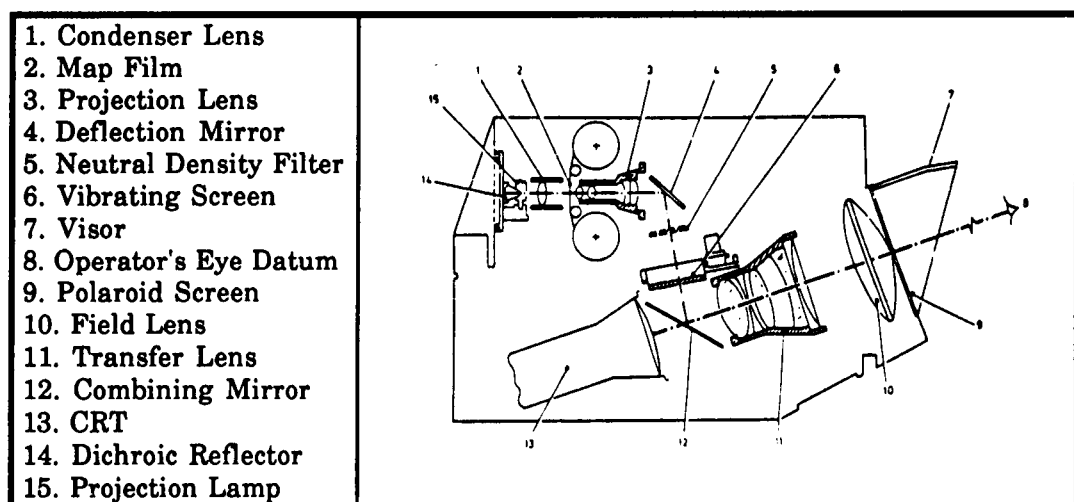


Figure 3.2. Combined Radar and Projected Map Display (CRPMD)

Main Computer (MC)

General. The data processing subsystem is designed to integrate the other two functional groups to provide storage, processing, and display of navigation, terrain following, and weapons release information. The navigation and weapon system is controlled by a high speed digital, general purpose LR-1432 microcomputer. Integrated circuits process incoming navigation signals and operator inputs to provide optimal data management. Data is processed by the mission computer and presented to the pilot on the Heads-Up Display (HUD) and to the navigator on any one of several multifunction displays. The computer uses a binary fixed or floating point 16-bit word stored in a 64K memory that can hold both program and data in the Erasable Programmable Read Only (EPROM) memory and Random Access Memory (RAM) storage. The Operational Flight Program (OFP) is composed of a set of software packages containing rules, procedures and instructions to store data, perform navigation and weapons aiming computations, and generate system responses. Program instructions and data are composed of 16-bit (fixed) and 32-bit (floating point) words which are stored in a 64K non-volatile, lithium ferrite core EPROM/RAM. Storage access times vary between 300 nanoseconds (ns) for semiconductor EPROM/RAM to 450 ns for core memory.

Equipment which receives and transmits data in a digital format is directly linked to the computer and is shown in Appendix A, Figure 5. Equipment which can not be directly linked to the computer is conducted through digital/analog and digital/discrete Interface Units (IFU1 and IFU2), also depicted in Appendix A, Figure 5. The forward cockpit is

generally served by IFU1, while IFU2 transmits data to the aft cockpit. Appendix B, Table 2, presents pertinent MC performance parameters. A continuous Built In Test Event (BITE) monitors all main computer interfaces and computer components.

Main Computer Components. The Main Computer is composed of the MC control panel, the central processor, the memory, two interface units, and the computer power supply. The MC control panel is located in the aft cockpit and provides power supply switching for the MC and the two IFUs. It indicates program load and fault detections to the navigator.

Interface Units. The interface units converts analog-to-digital and digital-to-analog signal conversion between the MC and the weapons system components. The direct memory access and program control is transmitted through 24 multiplexed input and 22 output channels. In the event of the loss of a single IFU, the remaining IFU can provide a limited interface. A 32 word per channel maximum transfer rate is used with a cycle rate of 2000 words per minute. Inputs are asynchronous, with each channel providing its own synchronization clock, and individual receiving equipment synchronizing to each channel received. Data is received in either a bit serial word or a non-digital format. Non-digital signals are grouped into two main categories, standard discrete and special discretess. Both are interfaced to the MC through the IFUs. Standard discretess are divided into four types as shown in Table 3-1. Special discrete are any binary signals not previously classified.

Table 3-1. Standard Discretes

Type	Description
Long Term	Pulse duration > 100ms. Used for long term system moding and status information. Transmitted on twisted pair unscreened lines.
Short Term	5ms to 100ms. Used for timing and blanking pulses. Transmitted in the same manner as long term pulses.
Switch	Provides switch position information. Transmitted on a single unscreened wire.
Indicator	Provides panel indications.

Operational Fight Program (OFP) . When loaded with the OFP and mission data, the MC performs program and operational tasks at an iteration rates ranging from 0.1 to 50 Hz. The OFP automatically commences operation when the MC power is initialized and provides the following functions:

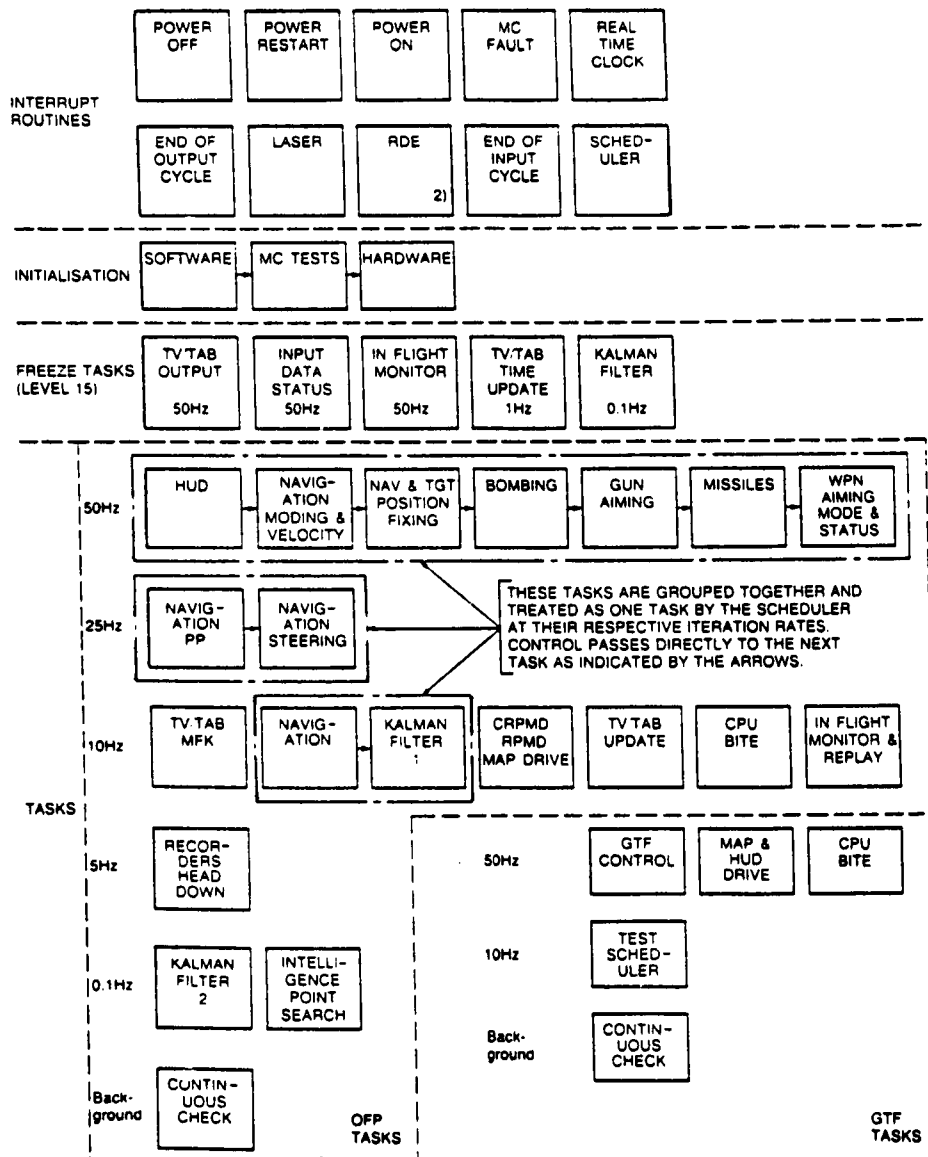
- a. Processing of vertical and horizontal navigation data from the active and the passive sensors, and the incorporation of position fixing data.
- b. Calculations of steering commands against the Automatic Flight Plan (AFP) or against a Manual Flight Plan (MFP) called up during flight or for an attack of a target.
- c. Sensor control during automatic and manual navigation fixing.
- d. Calculations of pointing angles for the displays and sensors and the processing of the angle, range and height data from those sensors.
- e. Coincident display of navigation fixing and weapon aiming data on the Television/Tabular (TV/TAB) display, CRPMD, and the HUD.

- f. Calculating the aircraft's present position based on the navigation mode selected. When the Main navigation mode is selected, the OFP calculates the 95% Circular Error Probable (CEP) position using a stored 19-state, Kalman Filter (KF) algorithm which estimates position based on the inputs from the Inertial Navigator, Doppler Navigator and position fixes. Position fixes which exceed the KF position estimate are recommended for rejection.
- g. Built-In-Test (BIT) monitoring and other functions not directly related to the terrain following navigation capability.

Computer Operation. The task packages that comprise the OFP are activated at predetermined iteration rates to provide control of the integrated navigation and weapon aiming functions as shown in Figure 3.3.

Additional flight data in the form of the AFP is loaded from magnetic tape using the Cockpit Voice Recorder (CVR). The AFP, consisting of up to 30 steering destinations (Waypoints, Fixpoints and Targets), is created on the Cassette Preparation Ground Station and stored on the magnetic tape cassette, the Program Storage Unit (PSU). In flight, the weapon officer can manually enter or alter data using the Multi-Function Keyboard (MFK) on the TV/TAB display.

The MC processes the navigation parameters and instructs the AFDS to supply steering commands to the CSAS. The computer automatically selects the optimum steering mode and will automatically revert to the next best mode.



OFP: Operational Flight Program

GTF: Ground Test Facility

Figure 3.3. Operational Flight Program Task Computer Iteration Rates

Inertial Navigator

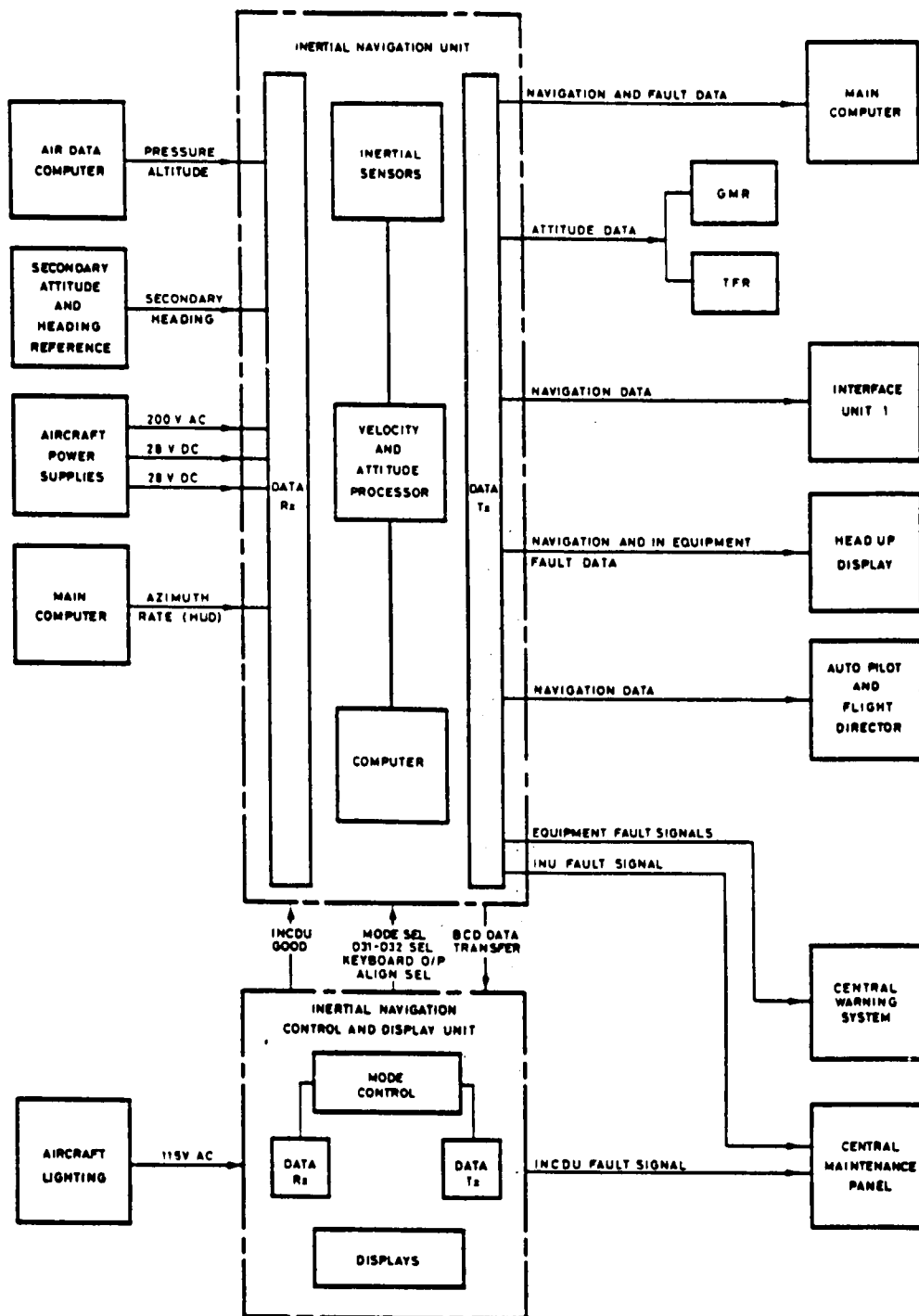
General. The Tornado GR Mk1 is equipped with a self-contained, semi-analytic worldwide, north-pointing FIN 1010 Inertial Navigator (IN) manufactured by Ferranti. The IN is a digital, floated, gyro-stablized, fully aerobatic system. It is designed to perform from latitude North 87.5° to 87.5° south with a slightly degraded performance capability when operated between 87.5° and 89.5° N and S. The FIN 1010 uses rate integrating gyros and pendulous accelerometers for a designed navigation accuracy of 1.0 NM per hour. IN operating limits are presented in Table 3-2.

Table 3-2. Inertial Navigator Operating Limits

Parameter	Limit
Operating Time Standby, Initial Position Insertion, Align Navigation	4 Hour Unlimited
Maximum Angular Rates Pitch Rate (0° to 80° nose up/down) Pitch Rate (80° to 90° nose up/down) Roll Rate Yaw Rate	± 60°/sec ± 35°/sec ± 270°/sec ± 200°/sec
Altitude (1)	-2,000 ft to +70,000 ftMSL
Emergency Battery Power	2 min

The system provides the MC, AFDS , TFR, and GMR system with dead reckoning position, aircraft pitch and roll angles, true heading, magnetic

heading (using inputs from the Secondary Attitude and Heading Reference (SAHR)), and North/South (N/S), East/West (E/W), and vertical velocities. In emergencies resulting from loss of the MC, the IN is designed to supply Horizontal Steering Indicator (HSI) steering to two stored waypoints and attitude information to the HUD. Inputs to the IN consist of pressure altitude from the ADC, magnetic variation and heading from the SAHR and azimuth rate from the MC. A functional block diagram of the IN is presented in Figure 3.4.



GMR: Ground Mapping Radar
 INU: Inertial Navigation Unit
 TFR: Terrain Following Radar

Tx: Transmit
 Rx: Receive

Figure 3.4. Inertial Navigator Functional Block Diagram

Components

Inertial Navigator Unit. The INU, located in the forward equipment bay, is a four gimbaled (3 Degree Of Freedom (DOF)) cantilevered, gyro-stabilized inertial platform mounted with N/S, E/W and vertical (Z) force feedback accelerometers to detect and measure aircraft accelerations. The orthogonally mounted accelerometers are aligned to True North and local vertical and synchros mounted on the gimbal axes provide attitude signals in pitch, roll, and heading. Barometric pressure from the Air Data Computer (ADC) is used to calculate the required gravity correction term to bias the Z accelerometer for the local gravity. Inertial platform data were processed by an IN computer and passed to the Inertial Navigator Control and Display Unit (INCDU) for display and to the MC, AFDS, GMR, and TFR.

Inertial Navigator Control and Display Unit. The INCDU located in the aft cockpit allows the navigator to enter present position and the emergency waypoint coordinates, monitor the type and status of the alignment and control the display of navigation data.

IN Operation. Selection of Standby on the INCDU mode selector knob applies power to the heater to raise and maintain the platform temperature to its designed operating temperature of +55° C. The mode selector is then switched to "Inertial Position Insertion" and electrical power is applied to

all IN components. Additionally, the system self test is initialized and present position latitude and longitude may be inserted. Selection of "Align" position will allow the platform accelerometers to align to true North and local vertical. Accurate IN alignment requires a heading input (accurate $\pm 10^\circ$) from the SAHR; or, if the SAHR is unavailable or out of limits, a manual entry may be made. Available alignment types and times are presented in Table 3-3.

Table 3-3. Inertial Navigation Alignment Times

Alignment Method	Description	Alignment Time (Minutes)
Normal	Longer time spent establishing azimuth datum for accurate navigation.	10-14
Rapid	Shorter fine alignment time. No rapid Heater so restricted to temperatures above 5 degrees C.	3-8
Memorized Heading	Based on memorized True heading for coarse alignment. (Aircraft can not be moved after shutdown)	3-6
Rapid HUD	Utilizes HUD fixing on surveyed point to provide initial position information.	3-6

Selection of the "Navigation" mode accepts the current alignment status and provides the primary attitude, velocity and position data to the MC for use in the primary "Main" navigation mode. Aircraft accelerations are sensed by the three accelerometers and the signal are fed to the platform interface where they are integrated to produce velocity pulses of 0.3 ft/sec. These pulses are used to update data stores accessed by the IN computer. Velocity parameters are calculated by the IN computer based on the stored

data and are fed back to the IN interface for distribution. Vertical velocities are measured by the platform synchros and are fed to the synchronization buffer for use by external equipment. The signals are also routed to the synchronization digital converter where the signal is digitized and fed to the data stores for IN computer updates of vertical parameters. A complete diagram of the IN supplied outputs is presented in Appendix A, Figure 6. During operation, IN position fixing is available through the radar, map or fly-over updates. Present position latitude and longitude may be updated individually or together.

Secondary Attitude and Heading Reference

The SAHR is comprised of the Gyro and Electronics Unit , Magnetic Detector Unit , and the Control and Remote Compensator Unit. It provides a primary attitude monitoring and cross reference during terrain following flight. In the event of an IN failure, the SAHR, in conjunction with the Doppler and MC, provide attitude and heading information for reversionary navigation and weapon aiming. The system supplies the following information to the weapon system:

- a. True heading and attitude to the MC and AFDS
- b. True heading and magnetic variation to the HUD
- c. Attitude data to the GMR and TFR
- d. True heading to the IN (for alignment)
- e. Magnetic heading to IFU1 for display on the HUD

Gyro and Electronics Unit. The Gyro Electronics Unit , located in the forward equipment compartment, was designed to output heading, pitch, and roll information. The unit contains electronics circuits and a four-gimbaled, gyro-stabilized platform from which attitude and heading information is derived. The platform is referenced to local vertical and receives earth and transport rate compensation terms derived from the MC. The compensation terms are calculated from Doppler, SAHR and MC velocities, and latitudes and are independent of an IN failure. If the MC fails compensation terms are not available, and the SAHR can only operate in the directional gyro (Compass) mode.

Magnetic Detector Unit. The Magnetic Detector Unit, located on top of the vertical stabilizer, contains a series of coils to measure the horizontal and vertical components of the earth's magnetic field. The horizontal component provides magnetic heading information. The vertical component includes compensation terms for the MC to correct detection errors resulting from the Coriolis and centripetal acceleration effects.

Control and Remote Compensator Unit. The Control and Remote Control Unit is the navigator's interface with the system. All SAHR controls, readouts and test/failure indicators are located on the panel. The remote compensator can be used to correct detected compass system errors.

SAHR Operation. The MC must be on and a correct present position entered to have compensation terms available to the SAHR system for alignment. Selection of the "Free" or "Slave" mode applies power, raises the operating temperature and erects the gyros. The gyro is erected to local

vertical and the azimuth is slaved to magnetic heading. In the "Slave" operating mode, the platform is slaved to the earth's magnetic field and is corrected for earth rate, aircraft rate, magnetic variation and is gyro stabilized. The "Free" mode separates the MDU output from the slaving loop and platform alignment is dependent on corrections for earth rate, aircraft rate and magnetic variation. The platform is gyro stabilized to local vertical. The slew control must be used to set true heading from any reliable source. The "Compass" mode derives true heading from the earth's magnetic field corrected for magnetic variation. The platform has no vertical stabilization. In the event of an IN failure, the MC automatically selects the Doppler + SAHR mode (DP+SR). This navigation signal flow diagram is presented in Appendix A, Figure 7. In this mode, Doppler horizontal and vertical velocities are transferred into a space referenced axis using attitude and heading information from the SAHR, providing the crew with ground speed, ground track and vertical velocity data.

Air Data Computer (ADC)

The ADC is a digital computer designed to calculate True Airspeed (TAS), Calibrated Airspeed (CAS), Mach number, pressure altitude, and corrected angles of attack for the IN, HUD, MC, and AFDS. The system uses dynamic pressure, static pressure, total temperature, and angle of attack probe inputs. Dynamic and static pressure inputs are routed through pneumatic transducers and enter the ADC as electrical signals with the barometric pressure entered through the HUD control panel. In

the event of an IN and Doppler failure, the ADC + SAHR mode is automatically selected. In this mode, ADC true airspeed is transferred into a space referenced axis using attitude and heading information from the SAHR. Ground speed and ground track are calculated using manually entered wind bearing and velocity stored in the MC.

Terrain Following Radar

Terrain Following Radar Components. The TFR is composed of the following major Weapons Replaceable Assemblies located in the nose radome as depicted in Appendix A, Figure 8.

Transmitter. The transmitter is designed to use a High Voltage Power Supply to generate high power radio frequency signals for transmission through the antenna. The transmitter also generates synchronization pulses for the TF computer and analog ranging signals used to trigger sensitivity time control circuits in the Antenna/Receiver.

Antenna/Receiver. The Antenna/Receiver is designed to route the transmitter RF output to the antenna, control the antenna scan coverage, and process all received signals to produce the video output pulses for TF computations. The Antenna/Receiver subsystem includes a guard antenna, waveguide and servo circuits, a sum channel, a difference and guard channel, video processing circuits, Intermediate Frequency (IF) amplifiers and mixers, antenna control actuators, BITE circuitry and the 270 mm TFR antenna. The antenna is designed to scan a window from -20°

to +10° in elevation and + 8° in azimuth during level flight with an increased azimuth coverage in the direction of aircraft turns. The gimbal mounted antenna is roll stabilized by the Radar Mount/Roll Unit when the Ground Mapping Radar (GMR) is operating.

Radar Mount/Roll Unit. The hydraulically controlled radar mount provides the main structural support and mounting interface for both the TFR and the GMR systems. The unit acts as an anti-vibration mount for all major radar components and provides the aircraft-to-radar interface for cooling air, and supplying electrical and hydraulic power.

Processor/Computer. The Processor/Computer (P/C) is a digital processor designed to produce the terrain following command signals for the AFDS. The P/C combines pulses received by the Antenna/Receiver, antenna elevation scan position, and aircraft flight data to generate the vertical steering commands used by the AFDS for automatic TF flight or the AFDS computer during manual TF flight. The P/C also provides computing and signal processing for the TFR equipment, azimuth and elevation command signals for the antenna actuators, input/output interface between the TFR and the weapon systems components, control operation of BITE functions, and generates the pilot's E-Scope displays.

Terrain Following System Operation

The TF previously described capability requires extensive RF signal generation and processing to accurately examine the terrain along the intended flight path of the airplane. The following operational description

provides a detailed description of the main aircraft interfaces, data requirements and processing techniques in the Tornado's existing TFR system. This information will serve to baseline aircraft inputs, output and interfaces available to the passive penetration system discussed later. Like the GMR, the TFR also operates in the Ku band and has only three operating modes: Readiness, Test, and Terrain Following. The TFR was designed to furnish TF commands to the autopilot and/or the flight director system permitting a low altitude, all-weather, closed or open loop flight capability. The pilot can fly the aircraft manually or he can select a desired clearance height and comfort level and fly in a coupled automatic terrain following mode.

Pulse Generation. Full operational performance of the TFR is available following a three minute warm-up period, however, required flight data may take up to 14 minutes as in the case of inertial navigator data. When activated the transmitter generates timing pulses, Master Trigger pulses for the C/P, and Receiver synchronization and blanking pulses. The correct pulse length is established in the pulse forming network and a frequency swept, high energy RF pulse from the magnetron. The RF pulse is routed through a protective load isolator and a directional coupler into the Antenna/Receiver. Automatic frequency control and sensitivity time control functions are performed and the pulse is radiated through the TFR antenna. The radiated pulse measures the range to terrain as a function of elevation scan angle and Monopulse Resolution Improvement pulses. The pulse is radiated in a $\pm 4^\circ$ azimuth scan

window; however, when the aircraft is in a turn, the antenna pattern is changed.

The radar volume changes from a 2-bar scan to a 4-bar scan covering approximately 14.5° , with the scan center rotated in the direction of the turn. This "lead into turn" technique is a function of aircraft turn rate and is designed to provide sufficient warning of terrain in a turn. The TFR system is capable of a maximum turn rate of 2° per second (scan center is offset 6.8° into turn) before the maneuver monitor indicator illuminates and a tone actuates indicating possible insufficient terrain clearance due to excessive turn rates.

Terrain Elevation Measurements. The RF energy from the antenna's two vertical main lobes is reflected from targets forming two signals at the antenna's comparator. The signals are processed as the sum of the lobe responses and the difference between the responses. The difference signal is in phase with the sum-signal for returns above the antenna boresight (zero for boresight). The greater the angle of the return above boresight, the greater the amplitude of the difference-signal. A hemispherical guard antenna pattern (similar to the sum-signal) is used to reject smaller sidelobe returns. The sum, difference, and guard signals are processed and passed through band pass filters to reject aliased frequencies. The signal is mixed twice to an intermediate frequency of 60 MHz and processed by a phase detector which produces a positive output pulse for above boresight (in-phase) signals.

Independent primary and secondary sources of aircraft flight data are supplied to the P/C Unit in addition to two logic signals from the AFDS.

Both logic signals are set to logic "0" in normal operation causing the TFR system to select IN data after comparison with SAHR/MC data. If the AFDS detects a failure in either data source, a logic 1 in that line instructs the P/C to use the alternate good data source. The TFR cannot select either data source based on its own monitoring; it can only activate the TFR warning if a fault is detected.

If TFR returns are insufficient, radar altimeter inputs can be processed to generate TF commands. This mode is inhibited when satisfactory TFR returns are present. The radar measured terrain range and elevation, aircraft flight data, and pilot selected ride setting and clearance height are processed by the P/C to generate g-command outputs. Table 3-4 presents the g allowed schedule assigned to each of the ride settings.

Table 3-4. Ride Settings and G-Command Schedule

Ride Setting	Desired Maximum Push Over Command	Desired Maximum Pull Up Command
Hard	+ 0.05 g	+3.0 g
Medium	+0.25 g	+2.0 g
Soft	+0.50 g	+1.5 g

The final TF command is limited to an airplane flight vector between +30° and -10°. A rate limit, equal to the pull-up and push-over maneuvers allowed by the selected ride setting, is also applied to the command. Finally, the signal is scaled as a function of aircraft velocity and selected clearance height, with the upper limits imposed to give maximum rate

values of +2.0g and -1.0g. The resulting command is a vertical maneuver command which defines the maneuver required to achieve the correct terrain following performance. This command is used for both manual and automatic TF. The g-commands are fed to the AFDS and the auto pilot to produce vertical steering commands for the flight director and tailplane movement if the autopilot is engaged.

Terrain Following Flight Procedures

Manual TF operation is available with power applied to the TFR system, and a desired ride and clearance height selected on the AFDS Control Panel. In this mode, the pilot manually responds to vertical steering commands presented with the HUD and ADI flight director symbology. Terrain following vertical steering indications are presented in Appendix A, Figure 9.

The automatic TF mode is engaged by depressing the TF button on the AFDS Control Panel, which enables the AFDS to send vertical steering errors to the CSAS computer to generate pitch commands as shown in Appendix A, Figure 10. During TF operation, the pilot monitors the Zero Command Line (ZCL) on the ESRRRD. The ZCL is the path of the TFR range and scan angle combinations which produce a zero g TF command. As shown in Figure 3.5, the shape and position of the ZCL will vary dynamically in space as a function of set clearance height, ride setting, aircraft velocity, and aircraft flight vector.

Regardless of the position or shape of the ZCL, obstacles penetrating it generate a pull-up command and obstacles below, but not touching the line, will generate a push-over command. The E-scope presentation is a visual profile of the terrain ahead which can be thought of as a "ski-tow" flight path profile. Figure 3.6 illustrates the regions of the flight vector commands for a typical elevation scan.

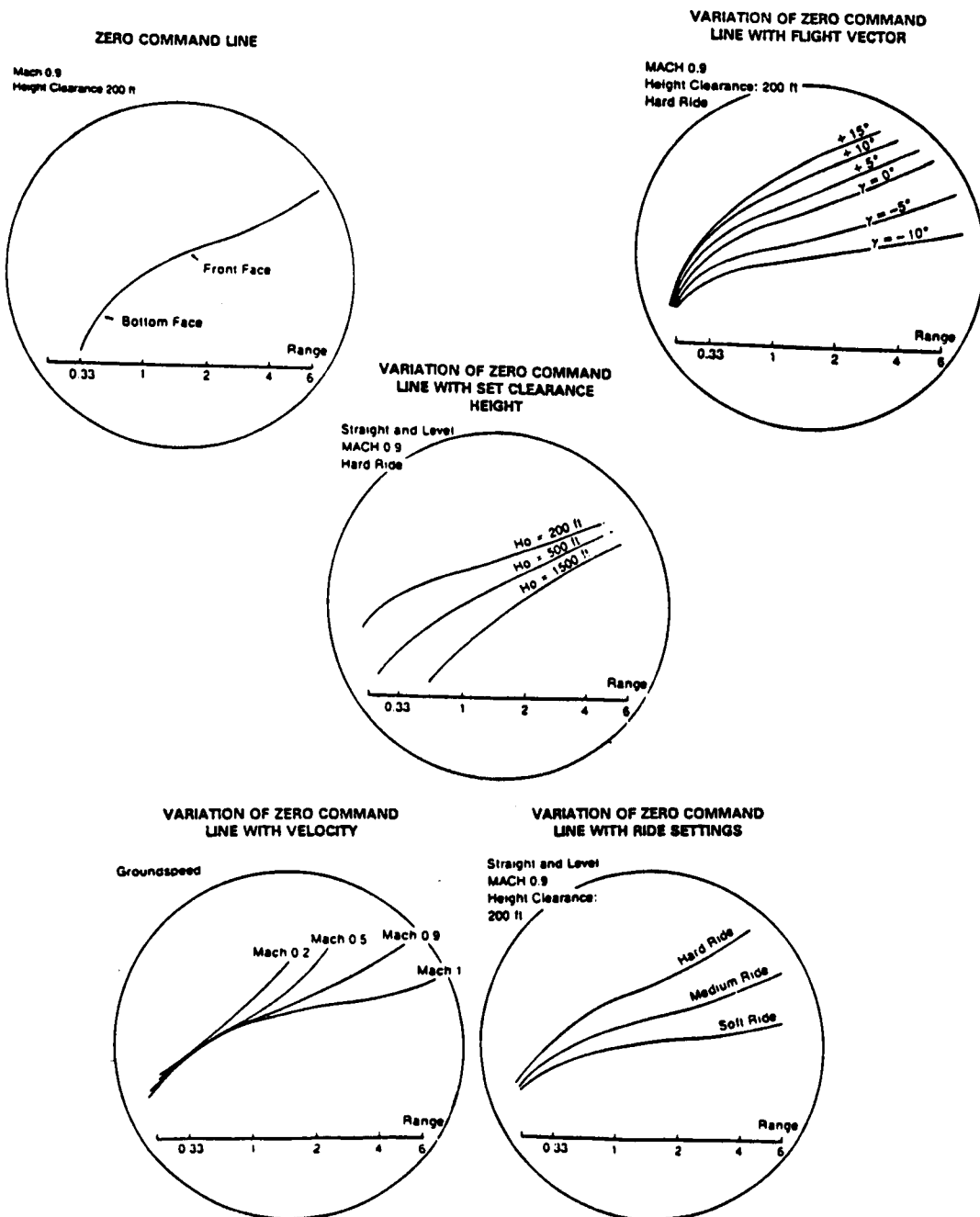


Figure 3.5. Zero Command Line Dynamic Variations

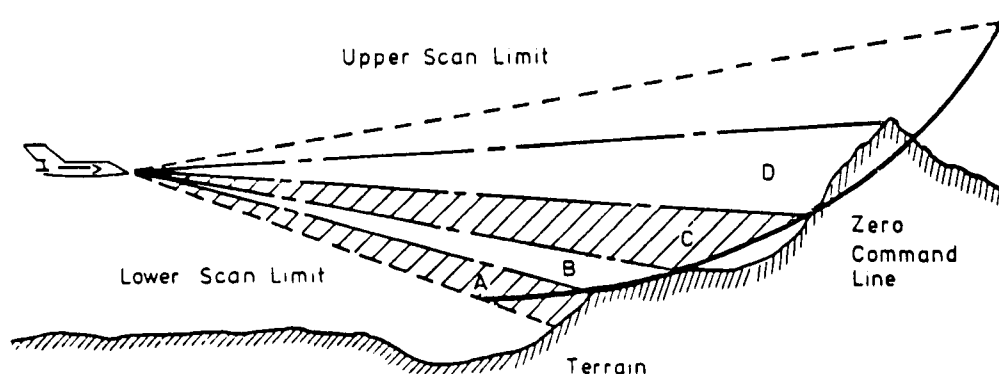


Figure 3.6. TF Command Generation

For the segment shown, push-over commands would be generated from radar returns in regions A and C. A zero command would be generated in region B and at the intersection of regions C and D. Pull-up commands would result from radar returns detected in region D.

Horizontal navigation selections are accomplished through the navigator's controls and displays in the aft cockpit. With all sensors operating, a navigation mode is selected on the NMCP which provide the MC with a source of ground speed for present position (PP) calculations. The MC calculates the aircraft's PP in both coordinate (based on the European Datum of 1950 coordinate system) and vertical planes. The present position horizontal and vertical channels can be updated singly or together by fixing routines. The MC automatically selects the next best navigation data sources in the event of any system failures. The calculated present position and stored mission data are used by the MC to generate steering commands for the HUD and TV/TAB. MFP and AFP are the two available steering types. When the MFP steering mode is selected, the MC

generates steering commands from the current present position to the next destination. In the AFP steering mode, the MC generates steering commands to intercept and maintain a track between the previous and the next destination.

Autopilot functions including Mach hold, heading hold, track hold (following azimuth steering commands), and desired velocity hold are all available during either manual or automatic TF operation. TF operation, however, can be thought of as decoupled steering with vertical steering commands taking precedence over and overriding horizontal steering commands until clearance criteria can be met. The operation of the TFR is continuously monitored by system BIT circuitry. A TFR system block diagram is shown in Appendix A, Figure 11.

4. PROPOSED PASSIVE SYSTEM

Introduction

Flight tests were conducted to assess the capabilities of the integrated navigation and attack system while operating in the Tornado's tactical environment. Their purpose was to evaluate the integrated navigation and weapons aiming system installed in the Tornado for the ground attack mission.

The two weeks of flight tests were conducted on an Italian Gr Mk 1 Tornado aircraft at the Practica Di Mare Flight Test Directorate, Rome, Italy in November 1987. The aircraft was configured with two external drop tanks (2800 lbs fuel), with two additional pylons, and full internal fuel (9800 lbs). The test aircraft, Bureau Number 7072, was representative of production Tornado GR Mk1 aircraft.

The evaluation included five hours of ground tests, three hours of flight simulator evaluations, and four 1.5 hour flights. Two low altitude terrain following missions (Appendix A, Figures 12 and 13) were conducted over varied topography such as water, level earth, rolling hills, and mountainous terrain. Three and one-half flight hours were accumulated on the two terrain following routes, flying at airspeeds between 360 KIAS and 0.9 IMN in the cruise and combat configuration shown in Table 4-1. Approximately 70% of the terrain following flight time

was conducted in the automatic mode with each TF ride setting being evaluated for a minimum of 30 minutes.

Table 4-1. Tornado Test Configurations

Configuration	Wing Sweep	Landing Gear	Flaps/Slats	Speedbrakes/Thrust Reversers	Thrust
Takeoff (TO)	25°	Down	Mid Flap/24°	In/Off	Reheat
Cruise (CR)	25° and 67°	Up	Up/0° or 11°	In/Off	TLF
Combat (CO)	45° and 67°	Up	Up/0° or 11°	In/Off	Idle to Reheat
Power Approach (PA)	25°	Down	Down/24°	Out/Off	TGS
Landing (LDG)	25°	Down	Full	Out/Off	Idle

1. TLF - Thrust for Level Flight.
2. TGS - Thrust to maintain Glideslope.
3. Reheat - Afterburner

The flight test results indicated that the "Tornado Integrated Navigation and Attack System in the Tornado GR Mk1 aircraft demonstrated good potential for the all weather attack mission" [3 Scanlan]. The system provided accurate navigation and smooth terrain following flight over a wide flight envelope and varied terrain. There were several minor deficiencies resulting from the moding of the terrain following system, but the technical performance of the system was satisfactory. Flight tests did, however, identify an increased susceptibility to ESM or ELINT receivers resulting from the operation of the Tornado's terrain following system. The constant emission of Ku band RF energy is easily detected and tracked by intercept receivers in the enemy's IADS.

Five possible alternatives to the use of the TFR were examined initially. The alternatives included using a GPS and digital terrain flight path generator, a laser terrain detection system, a navigation FLIR, a Terrain Contour Matching (TERCOM) system, or a Low Probability of Intercept (LPI) radar. A systematic, multi-attribute evaluation of the five systems was conducted using that decision analysis tool to rate attributes of a terrain following system and rank the proposed systems [10 Canada]. Eighteen naval aviators ranked 12 attributes of a supplemental terrain following system shown in Table 4-2.

Table 4-2. Attribute Ranking From Aviator Questionnaire

Number	Attribute	Score	Rank
1	Operating in all weather or jamming environment	68	2
2	Passive (No RF emissions)	72	3
3	Accurate and safe	55	1
4	Operates over all terrains	85	5
5	Operates in full flight envelop	81	4
6	No large weight or size penalty	119	6
7	Easily integrates with hardware	127	7
8	Easily integrates with software	153	11
9	Affordable	145	9
10	Rapid integration into platform	141	8
11	Low technological risk	175	12
12	Internal to platform	156	10

Although safety and accuracy of a system ranked as number one, this attribute was assumed by the author to be a given for the integration of any of the proposed systems and was therefore discounted from the list. From the remaining attributes, the top five were selected and weighted to reflect the importance of the attribute to the system. Personal experience and the overall ranking scores were used to establish the relative weights presented in Table 4-3.

Table 4-3. Normalized Attribute Weights

Number	Attribute	Weight [=W(.)]	Normalized Factor Weight [= W(.) * 100 / $\Sigma W(.) = W_i$]
A1	Operates in all weather or jamming environment	100	29
A2	Passive (No RF emissions)	95	28
A3	Operates in the full flight envelop	60	18
A4	Operates over all terrain	50	15
A5	No large weight or size penalty	35	10
		$\Sigma = 340$	$\Sigma = 100$

In the final step of the analysis, a numerical value between 1 and 10 was assigned to reflect the degree each proposed system satisfied each attribute. The resulting weighted evaluation of all the proposed alternative indicated the desirability of two systems, the favored GPS and digital terrain system and the LPI radar system. Although both systems remained comparable when rated against the remaining six attributes, *GPS was selected because it also provided added navigation and sensor pointing benefits.* Table 4-4 presents each alternative with its associated attribute scores, weight evaluations, and final weighted score, highlighting the ranking of alternatives.

Table 4-4. Calculation of Weighted Scores and Alternative Ranking

No.	Alternative One		Alternative Two		Alternative Three		Alternative Four		Alternative Five	
	Score	Wgt	Score	Wgt	Score	Wgt	Score	Wgt	Score	Wgt
A1	8.5	25	6.5	19.5	6.5	19	8.5	25	7.5	22
A2	10	28	8.5	24	10	28	8	22.5	9	25
A3	8.5	15	8.0	14.5	8	14	7	12.5	8	14.5
A4	10	15	8.5	13	8.5	13	5.5	8	9.5	14
A5	9	9	6	6	8	8	8	8	9.5	9.5
	$\Sigma = 92$		$\Sigma = 77$		$\Sigma = 82$		$\Sigma = 76$		$\Sigma = 85$	

Attribute Number:

A1: All weather/jamming operation

A2: Passive

A3: Full flight envelop

A4: Over all terrains

A5: No large weight/size penalty

Alternative Number:

1: GPS/digital terrain data

2: Laser detection system

3: TERCOM

4: Navigation FLIR

5: LPI radar

The selected Proposed Passive Penetration System (P³S) consists of a GPS set, a digital terrain database, an additional computer, and the associated interfaces and controls required to integrate the system with the existing Tornado TF and navigation suite. The passive terrain following system incorporates the long term position accuracy of the GPS into the existing Tornado navigation system. The aircraft's position and flight path over the digital terrain database are maintained by the navigation system and feed forward and feed backward algorithms are used to scan digital terrain data and generate the TF commands previously created by the TFR.

A five step system integration methodology was used to define the need, assess the potential, and outline an implementation scheme for the

proposed GPS TF system [11 Hudak]. This approach attempts to optimize the system's capabilities by matching the best GPS integration scheme with the design requirements and the capabilities of the host vehicle. The system design approach, presented in Figure 4.1, uses a series of questions to refine and focus each step of the integration process.

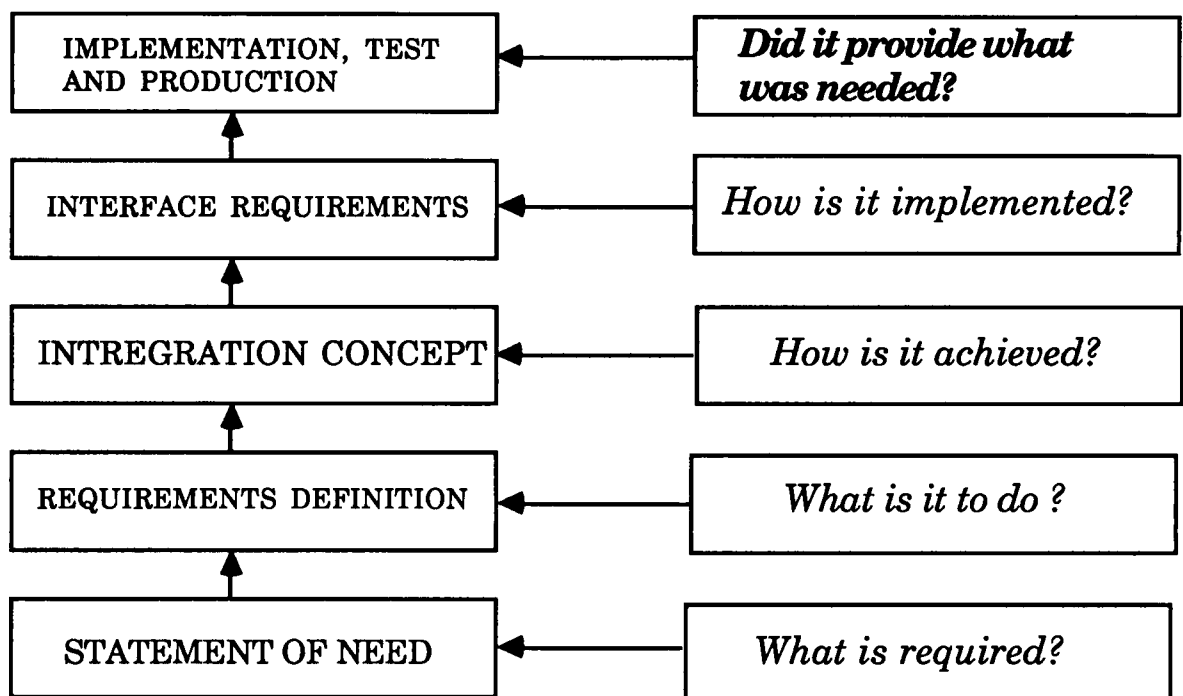


Figure 4.1. Steps of the GPS System Integration Process

Statement of Need

The statement of need for a passive terrain following capability is derived from Tornado flight test results. The Tornado's terrain following capability, although suitable, requires the TF radar to transmit during all terrain following flight, increasing its detectability by many of the new threats. A representative generic radar operating at a frequency of 15GHz, with a pulse repetition frequency of 200 pps, a 40db antenna gain and a peak radiated power of 5 watts, can detect a 1m^2 target at approximately 22.5km. A simple form of the radar range equation 4.1 makes it evident that the maximum range of a returned signal from a transmitting radar (two-way) is a factor of the fourth root of a number of radar and target parameters.

$$R_{\max} = \left[P_t G A_e \sigma / (4 \pi)^2 S_{\min} \right]^{1/4} \quad (4.1)$$

where

P_t = transmitted power, watts

G = antenna gain

A_e = antenna effective aperture, m^2

σ = radar cross section, m^2

$S_{\min}$ = minimum detectable signal, watts

Rearranging equation 4.1 to reflect the intercepted one-way signal path yields equation 4.2. It is evident that because the range is only a factor of the square root of the radar and target parameters, the intercepted signal is detectable by ESM or ELINT systems at far greater ranges. The peak power received by one of these systems is given by equation 4.2 [10 Hoisington].

$$S = \frac{P_t G_t g^2 G_r \lambda^2}{(4 \pi R)^2 L_p} \quad (4.2)$$

where

P_t = peak radar power output

G_t = radar antenna gain toward intercept receiver

g^2 = path gain relative to free space ($0 \leq g^2 \leq 4$)

G_r = gain of receiving antenna toward radar

λ = wavelength

R = distance from radar to intercept receiver

L_p = polarization mismatch factor ($L_p \geq 1$)

Assuming a co-located intercept receiver and target, equation 4.3 gives the ratio of the two-way path signal strength to the one-way path signal strength and characterizes the intercept receiver's significant detection advantage.

$$\frac{(\text{Power/Unit Area})_{\text{target}}}{(\text{Power/Unit Area})_{\text{radar}}} = \frac{4 \pi R^2}{\sigma g^2} \quad (4.3)$$

where

σ = target radar cross section

R = Range to target

This means that a generic intercept receiver with a nominal bandwidth of 25 MHz and a -84 dBm sensitivity for a signal-to-noise ratio of 20, and operating with a small amount of free space attenuation, could detect the previously described airborne radar's mainlobe, at approximately 125 km. Additionally, threat ESM systems like the Soviet Ramona, French Selina, or

Hungarian Mervin, may use larger effective antenna capture areas, apriori knowledge of the radar signal to narrow frequency search bands, lower gain thresholds and employ signal processing techniques (i.e. pulse integration) to gather signals from greater ranges. The intercepted signals can then be analyzed, categorized, and associated with a probable target type to provide target identification and localizing information for enemy threat systems in the IADS.

The IADS can be pictured as a computerized Local Area Network (LAN), designed to rapidly distribute target information to a number of threat nodes. Individual bits of information can be collected and processed by the IADS to create target tracks and files. Similar to a LAN, the IADS can, when operating effectively, offer processing gains on the order of 1.5 to 4 times the individual system's. Denying the enemy early warning and information about a target can greatly reduce the effectiveness of his integrated system. The enemy is unable to localize a threat axis or commit assets to engage the attackers. Individual weapons are forced to work autonomously to engage a target without timing or directional cueing. This denial of early information also subjects the threat systems and the IADS to the active and passive countermeasures supporting the Tornado strike aircraft. These systems (jamming, harm, decoys) are designed to provide additional support of the low altitude penetrators by denying or destroying threat system acquisition and targeting capabilities.

A passive penetration capability permits low altitude terrain masking flight without the use of the TF radar. Early interceptions of the attacking aircraft RF emissions are reduced or eliminated, improving the Tornado's penetration capability and enhancing its survivability.

Requirements Definition

Many of the attributes or capabilities of the P³S were defined during the multi-attribute analysis and can be restated to define what the system is designed to do. The proposed modification to the Tornado Integrated Navigation and Attack System should permit the aircraft to safely and accurately maintain low altitude terrain following flight without the use of high energy RF emission from the TFR. By using an alternate terrain information source and GPS precise position information, the P³S can provide a coupled horizontal and vertical navigation capability. The system must be capable of operating in the same high threat density, European combat theater the Tornado is currently deployed in, and should also be effectively over water or land. Hardware modifications should be minimized and the system should utilize as much of the existing avionics architecture as feasible. The system should operate in any part of the world and be compatible with the Tornado's flight envelop. The aircrew should be able to fly the system manually or automatically in differing weather and electronic countermeasures environments. Terrain following capabilities should integrate with all navigation and weapons aiming modes. Aircrew should be able to monitor system performance and be able to rapidly detect any degrades or failures. Additional space, cooling, and electrical requirements should be minimized. The P³S should meet or exceed the operating and performance characteristics of the existing TFR system. The Tornado TFR's and the P³S's major characteristics and the limits are compared in Table 4-5.

Table 4-5. Radar Terrain Following Characteristics

Parameter	Terrain Following Radar	Passive Penetration System
Clearance Height	200 to 1000 ft AGL	Aprox 300 to 1000 ft AGL
Ride Control	Soft,Medium, Hard	Soft,Medium, Hard
Turn Rate	Max 2 deg/sec	Undefined, no less than 2 deg/sec
Cooling	Conditioned Bleed Air	Conditioned Bleed Air
Electrical	200V, 400Hz 3-phase AC	200V, 400Hz 3-phase AC
Navigation	Vertical	Coupled
Weather Capability	Limited in heavy rain	Unlimited
Jamming Capability	Good, Frequency agile	Excellent, Jam resistant
Detectability	High	None
Backup Operation	None, Climb Required	Degrade to Radar TF

Integration Concept

The two main components comprise the aircraft portion of the P³S with one additional element replacing to the ground mission planning station. A digital terrain database, stored in a new aircraft computer, provides a digital 3-dimensional map of the terrain along the aircraft flight path. The second component, an integrated GPS set, provides a relatively accurate position and velocity data which is used by the navigation computer to calculate clearance heights and generate the required TF commands. The ground based, automated mission planning system would be a computerized system replacing the magnetic chart registration table currently used in the aircraft.

An integration approach offering the greatest capability would add the GPS set and replace the existing MC with a faster model with expanded memory. The entire set of cockpit displays (CRPMD and TV/TAB) would be replaced with digital, color multi-function displays capable of presenting digital maps. This approach would initially be extremely expensive and complicated requiring extensive hardware changes as well as modifications to a majority of the software and OFPs. This scheme would be a near complete redesign of the aircraft avionics and would not meet the objective of incorporating an enhancement while minimizing aircraft changes.

The preferred integration scheme would use the existing LR-1432 computer to continue the overall mission data processing but an additional computer would be added, primarily, to store and process the digital terrain data. Both computers would interface through the IFUs, with the new second Mission Computer (MC2) providing redundant mission essential calculations and primary processing for passive terrain following and navigation. However, in the passive mode the MC2 would control film map and digital terrain data registration and drive the P³S displays.

Radar video and topographical charts (combined or individually) would continue to be displayed on the CRPMD in the active mode and charts only would be displayed when operating passively. The existing Digital Scan Converter (DSC), located in the forward equipment bay, converts GMR low refresh-rate analog radar video into high refresh-rate, 625-line, 50 Hz raster format for display to the navigator. Based on velocity, heading, and clearance height data from the MC, the DSC provides memory, timing, control, symbol positioning, and slant-to-plan range correction for radar

video/projected map registration. These DSC functions could be transferred to the MC2 and the DSC could be eliminated, offsetting some of the additional weight gain and space loss necessitated by the second computer. The automated mission planning system would use the same digital data bases incorporated in the P³S and would provide a rapid, computer aided low level planning aid. Digital terrain data would be loaded into the computer using the existing mission cassettes or a new Compact Disc (CD) interface.

To understand how the P³S would meet the defined goals, the elements of the two major P³S components are described, followed by the proposed system's operation, an analysis of the system's error sources, and a recommended integration configuration.

Digital Terrain Elevation Data. The Defense Mapping Agency (DMA) in the US, France, and other countries produce digitized terrain products for commercial and military use. Several production methods are used including digitizing overhead stereo-pair satellite imagery, digitizing charts and incorporation of actual survey data. Each producer attempts to minimize error sources, however, the products contain errors resulting from the registration and rectification of imagery and mensurated coordinates. DMA produces and maintains a Digital Land Mass System (DLMS) database which is the source of a product called the Level 1 Digital Terrain Elevation Data (DTED). DTED is used only as an example of the class of product that would be required for the P³S.

DTED data are in a uniform matrix of terrain elevation values taken from ground elevation posts [14 DMA]. Level 1 data is derived from

elevation posts every three arc seconds or approximately 300 ft. Level 2 data, which is not currently produced, would contain measurements taken every one arc second. Level 1 and level 2 data would have the same measurement accuracy specifications; however, due to the additional data points, Level 2 data would offer a finer terrain granularity but would cost the user greatly increased storage and processing time. The DTED Level 1 accuracy objectives specified by DMA as well as typical accuracies obtained by using the DMA's best information sources are shown in Tables 4-6 and 4-7.

Table 4-6. Specified Digital Terrain Data Accuracies

Type	Level	WGS Horizontal	MSL Vertical
DTED	1	130 m	± 30 m
DTED	2	130 m	± 30 m

Table 4-7. Typical DTED Accuracy Ranges

Measurement	Accuracy	Reliability
Absolute Horizontal	25 - 35 m	90% CE
Point-to-Point Horizontal	15 - 30 m	90% CE
Absolute Vertical	± 25 - 30 m	90% CE
Pont-to-Point Vertical	± 20 - 25 m	90% CE

These accuracies represent the type of quality required for a digital terrain base to be used for navigation. DTED uses a geographic coordinate reference system. The World Geodetic System (WGS-72) provides the

horizontal datum for DTED with Mean Sea Level used as the vertical datum. Data are stored in cells that contain the terrain elevation data measured in meters and the latitude and longitude of the referenced point. Each cell contains between 201 and 1201 Elevation Data Records. The digitized terrain data format and a segment of digital terrain are presented in Figure 4.2 .

Accuracy statements are calculated for each DMA product and are digitized in each cell's header. The accuracy of the product results from the method of processing and is independent of the data resolution or the granularity. Since each point is measured and processed separately, the accuracy is independent of all the other points and increasing the density of points will not improve the accuracy or resolution of information in it. To provide additional safety and performance for low altitude terrain following flight, the DTED Level 1 type data would need to be augmented with another DMA product called Vertical Obstruction Data (VOD). VOD and similar products contain discrete position and height information on both man-made and vegetation obstructions that extend into low altitude flight levels. The density of the data is dependent on the actual density of obstructions in the area. In the DMA product obstructions separated by less than 1000 feet are treated as an aggregate feature. Each obstruction record contains a description of the type, category location and dimensions of the obstruction as well as the accuracy of the obstruction height. Vertical obstructions are classified as either a point, a line, or an area, as depicted in Figure 4.3.

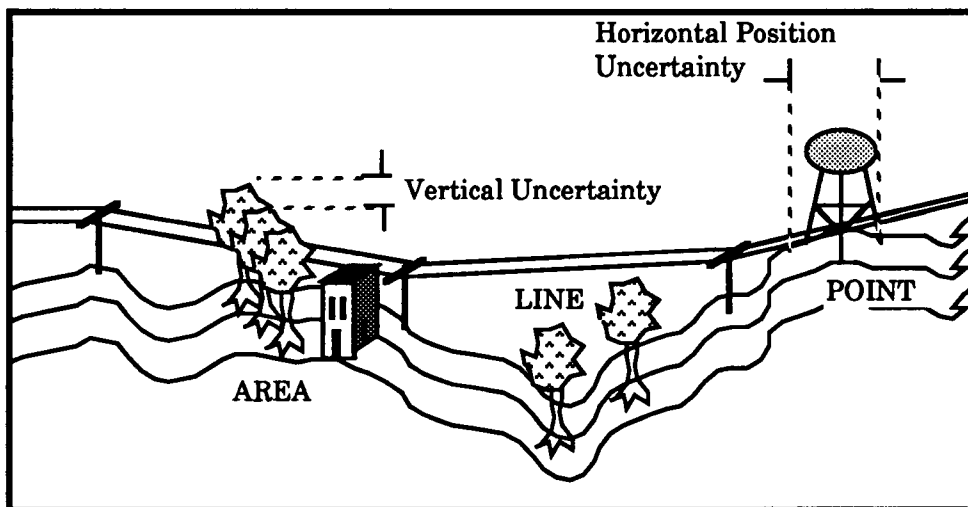


Figure 4.3. Vertical Obstruction Types and Uncertainties

Points are normally separated by sufficient distances to permit flight between them. Lines include features like bridges, power lines and high tree lines. Lines can pose an effective wall to a low flyer and must be overflowed to avoid a high probability of ground clobber. The final obstruction type is the area which has sufficient vertical obstruction density to be treated as a single area which can be flown over at a higher altitude or circumvented at a lower altitude.

Both sets of digital data are available on magnetic tape. However, DMA and other possible suppliers are also adopting a new Compact Disk (CD) format that would permit a much greater storage capacity and would offer a faster computer interface with the P3S.

Global Positioning System Overview.

The Global Positioning System is a space based satellite navigation system. Following early interest in similar systems in the 1960s, the GPS was developed in the early 1970s under a joint Department of Defense (DoD) and NATO program. GPS is composed of three system segments - a Space segment, Control segment and a User segment.

The Space segment consists of a constellation of 24 navigation satellites placed in 10,900NM, 12-hour orbits. The satellites, launched from NASA shuttles or Delta II rockets, are positioned in six orbital planes, each inclined 55° . Three operational satellites plus an active spare will be positioned in each orbit in non-uniform "optimized" phasing to provide worldwide navigation coverage. To maintain this coverage, the Satellite Vehicle (SV) must be visible to a ground receiver. This visibility is measured as a mask angle (DoD requires 5°), which is the elevation angle from the local horizon below which the SV is unusable and normally defined as a function of a zero dbi antenna gain. The loss of the space shuttle Challenger in 1986 delayed the planned launch schedule and currently there are only 12 healthy (17 total) SVs in orbit with the remaining satellites to be in place in the early 1990. Table 4-8 is a summary of significant GPS characteristics.

Table 4-8. GPS Characteristics

Parameter	Characteristic	Description
Satellite Constellation	Satellites	21 satellites plus 3 active spares Satellites broadcast signals autonomously
	Orbit	6 planes with 4 satellites per plane 55° inclination, 12 hour period, 10,900 NM altitude
Signal Structure	Frequency	Dual L-band (1575.42 MHz, 1227.60 MHz)
	Digital Signal	Spread spectrum PRN, C/A code at 1.023 MHz, P code at 10.23 MHz, Continuous navigation message at 50 Hz
	Other	CMDA signal separation
Coverage		Worldwide

The Control segment is composed of five monitoring and three transmitting earth-based control stations. The types and locations of the control stations are presented in Appendix B, Table 3. All control stations monitor the SV signals collecting range and environment data. The Master control station, located in Colorado, monitors and tracks SV navigation estimates in the form of ephemeris, clock, and satellite health data. This data is used to control and schedule the SV constellation by transmitting updated navigation data and commands.

The third portion of GPS is the User segment. The User Equipment (UE) consists of an antenna, receiver/processor, display and control unit, and power supply unit. This operating set receives and processes the time and position data from the satellites and calculates accurate position and velocity measurements for the host vehicle. There are several types of user sets available based on the host vehicle's size, weight, and anticipated dynamic environment [15 Bjornsen]. A single channel set is capable of tracking a single satellite at a time and must sequence through other satellites to accurately determine the user's position. It is the smallest,

lightest set, and requires the least power to operate. Where the single channel receiver is suitable for a man-portable applications, the 2-channel UE is suited to a more dynamic environment such as shipboard operation. Although larger than the 1-channel set, the 2-channel set offers two correlators and is capable of simultaneously tracking two satellites. The final receiver is the 5-channel set which can maintain a navigation track on four satellites while maintaining a fifth peripheral track for acquisition of an alternate satellite. The fifth channel can be used for a concentrated satellite search, reacquisition of a lost SV, handover to a newly acquired SV, or to aid in calculating ionospheric corrections. The 5-channel receiver is capable of the fastest SV acquisition and sustains its accuracy throughout a large dynamic maneuvering envelope. The other UEs are inherently as accurate as the 5-channel set, but are not able to sustain the accuracy in dynamic environments.

Fundamentals of Ranging

Due to the precise nature of physics and orbital mechanics, the exact position of a satellite can be accurately tracked and predicted at any time. If a radio message is transmitted from a known satellite position and the receiving station knows the time the message was sent, the user can estimate a range to the satellite based on how long the signal took to reach the receiver. To measure this time, the satellite and the receiver must

simultaneously generate a pseudo-random digital code. By matching the transmitted code with the receiver's code, the system can calculate the time since a specific portion of the code was generated. The longer this time delay, the farther away the user is from the transmitting satellite. With knowledge of satellite orbital and ephemeris parameters and given the velocity of light, Equation 4.4 can be solved to yield a distance or range to the transmitting satellite.

$$PR = c * \Delta t_{\text{meas}} \quad (4.4)$$

where

PR = Pseudo-range = distance

c = speed of light (approximately 186,000 mph)

Δt_{meas} = time from transmission time to transmission receipt
($T_R - T_T$)

The solution to Equation 4.4 provides a range to the SV but no bearing information. With only this ambiguous information, the user knows only that he is located somewhere on a sphere of a given radius as shown in Figure 4.4.

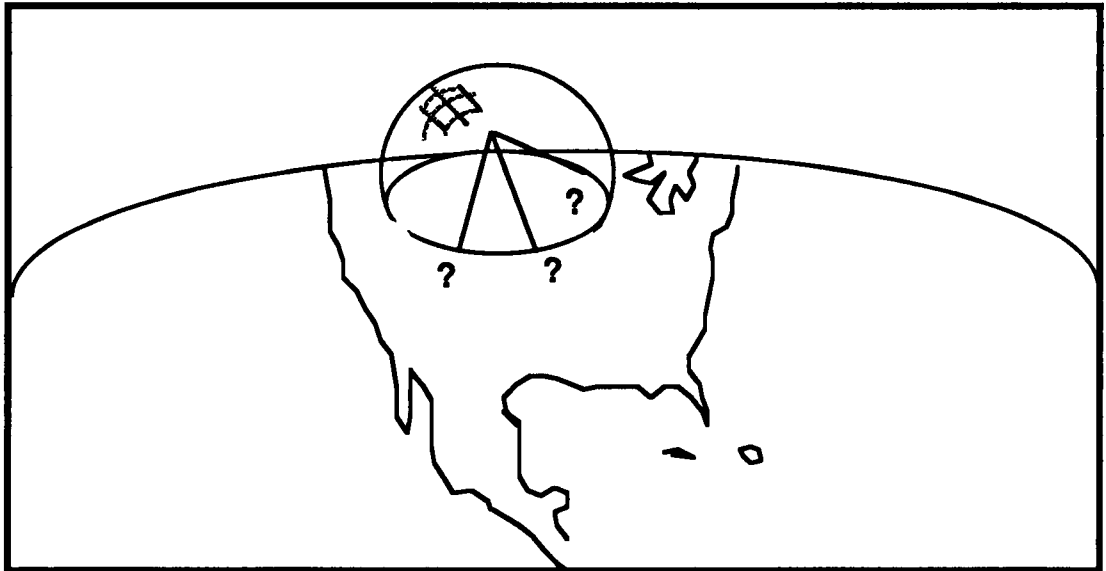


Figure 4.4. Single Satellite Position Ambiguity

Precise ranging requires time measurements accurate to a nanosecond (10^{-9} second) [Reference 16]. The measured time can be described as the sum of the actual time and a clock error, Equation 4.5.

$$\Delta t_{\text{meas}} = \Delta t + \Delta t_{\text{bias}} \quad (4.5)$$

where

Δt_{meas} = measured signal transit time

Δt = actual transit time of signal

Δt_{bias} = clock error time bias

These clock errors (Δt_{bias}) in the user's receiver translate into a ranging error as depicted in Figure 4.5 and Equation 4.6 .

$$PR = R_u - R_s + B_u \quad (4.6)$$

where

R_u = User position in WGS-84 Earth Centered Earth Fixed (ECEF) reference frame

R_s = Satellite position in WGS-84 ECEF reference frame

B_u = Range Bias

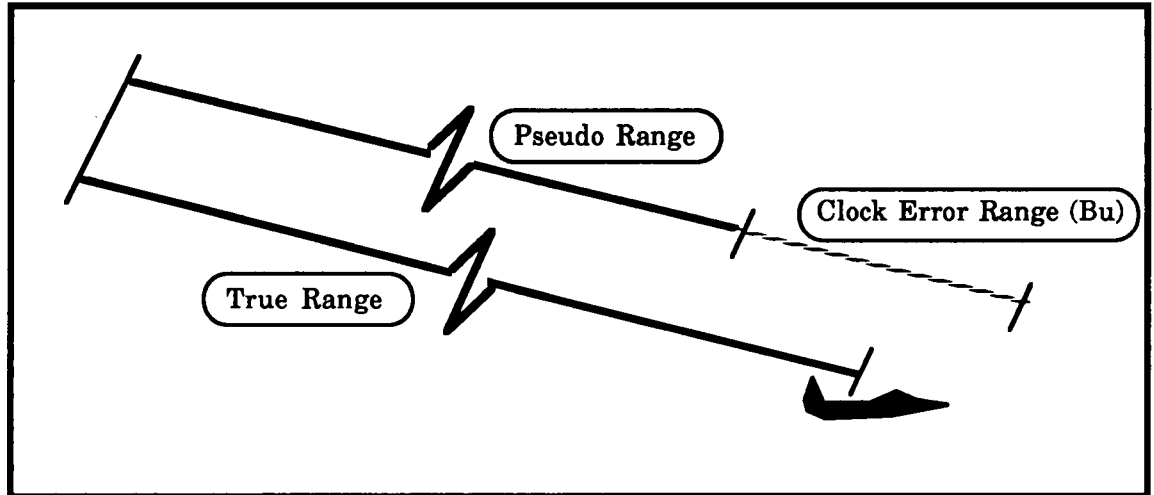


Figure 4.5. GPS Range Uncertainty

To fix a two dimensional position, two satellites would be sufficient if there was no clock bias error. Using the simplified two-dimensional case shown in Figure 4-6, it is apparent that precise positioning is unresolvable without a good estimate of the clock bias and the related ranging error. This added variable requires a third satellite to resolve the position ambiguity. Solving four simultaneous equations using a fourth satellite permits a position fix in three dimensions and the calculation of host vehicle velocities. Figure 4.7 depicts a typical GPS navigation position fixing problem involving four satellites and four unknowns.

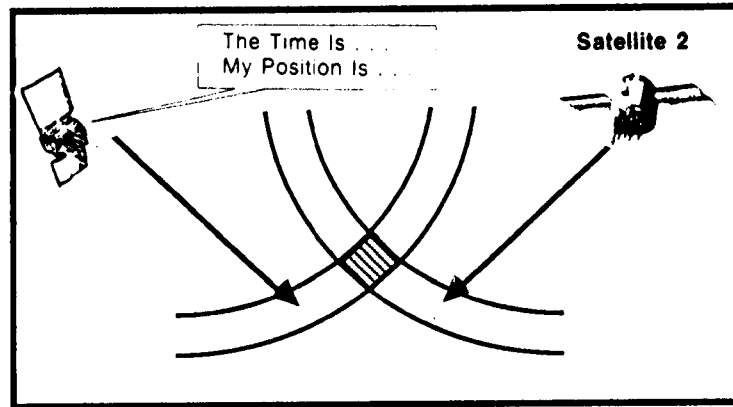


Figure 4.6. Two-Dimensional Example of Satellite-to-User Range Ambiguity Due to Clock Error

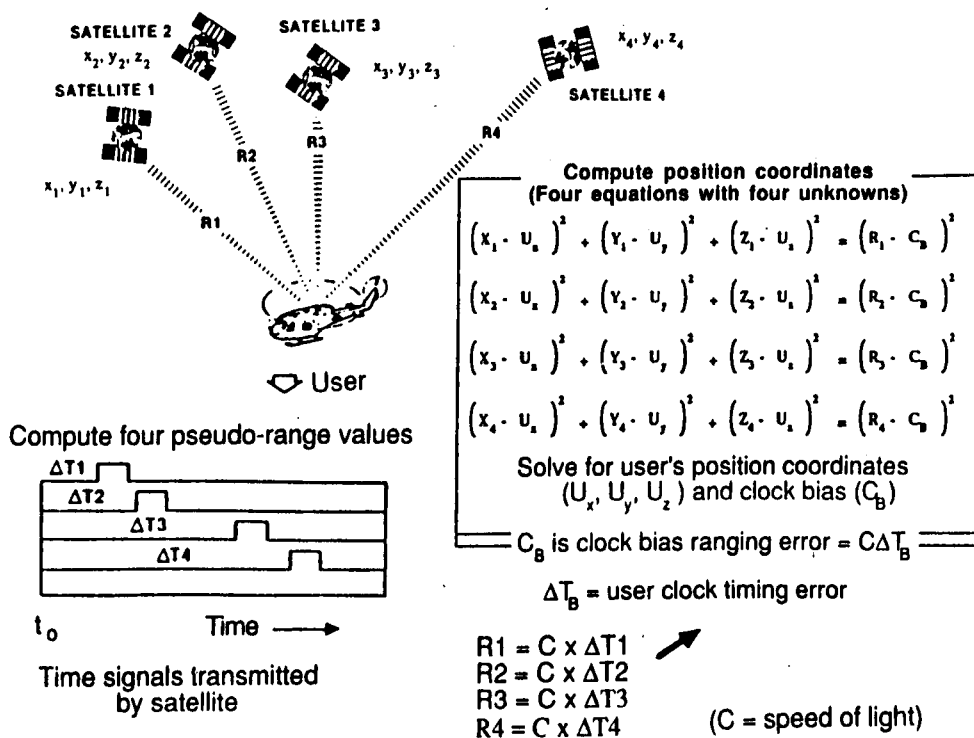


Figure 4.7. GPS Navigation Solution

GPS Satellite Operation. GPS satellites contain highly accurate internal Rubidium or Cesium atomic clocks to maintain the timing accuracies necessary for accurate navigation. System time and other SV data are transmitted on a GPS signal composed of two discrete signals. The L1 signal is broadcast at a 1575.42 MHz and carries a Precision (P) code, Coarse Acquisition (C/A) code, and navigation data. The L2 signal is transmitted at a frequency of 1227.60 MHz and carries the P code and navigation data or the P code alone. Both signals are circularly polarized and are transmitted in phase quadrature. The C/A and P codes are Pseudorandom Noise (PN) codes with the characteristics listed in Table 4-9. The modulation techniques used by the satellites to combine the signals and the resulting L1 and L2 structures are depicted in Figure 4.8.

Table 4-9. C/A and P Code Characteristics

Parameter	C/A Code	P Code	Data
Chipping Rate	$1.023 * 10^6$ BIT/sec	$10.23 * 10^6$ BIT/sec	50 BIT/sec
Spatial Length (per BIT)	960 ft	96 ft	3720 Mile
Repetition Interval	0.001 sec	7 Day	Not Applicable
Code Type	Gold Code	280 Pseudo Random Codes	Not Applicable
Total No. of Codes.	37 Unique Codes	37 Seven-Day Sections	Not Applicable
Special Properties	Easy to Acquire	Slightly More Accurate Nav Resistent To Jamming and Spoofing. Rejection of Multipath.	Provides Handover From C/A To P Code. Ephemeris Data and Clock Correction. Rejection Of Multipath.

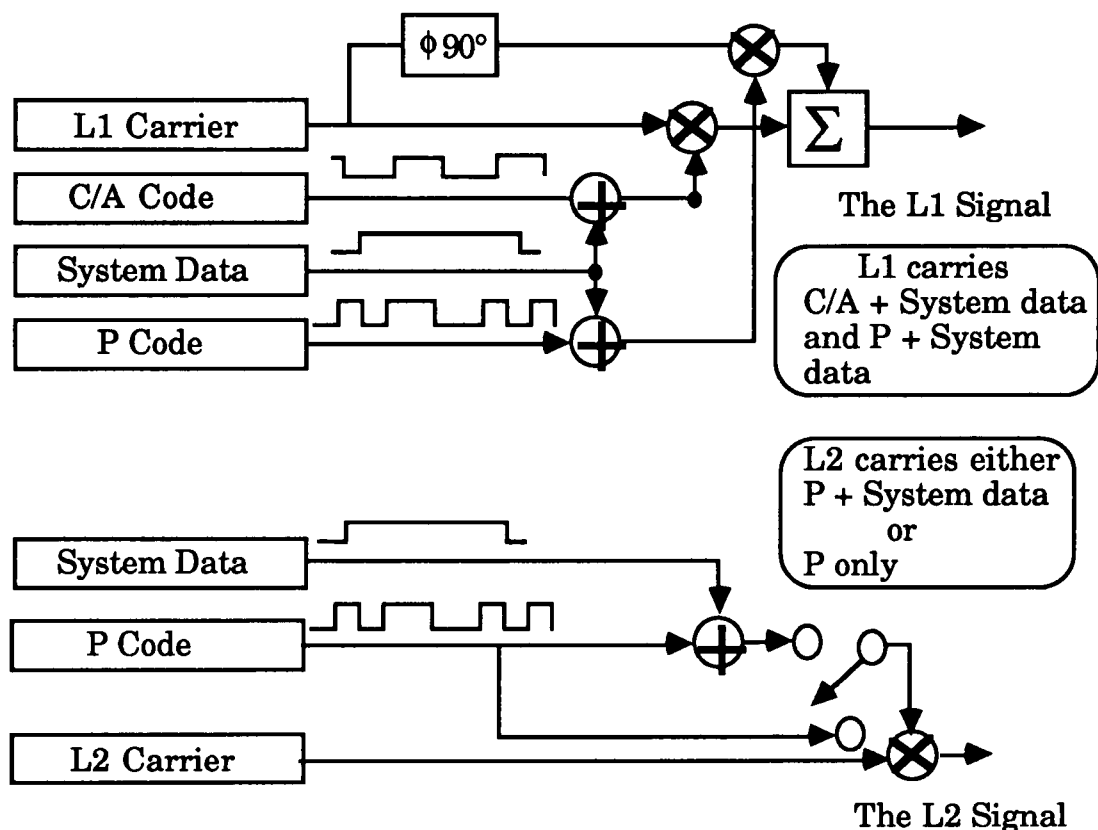


Figure 4.8. GPS Satellite Signal Modulation Techniques Combining Signals for Transmission

The Standard Positioning Service (SPS) is the operating mode available to civilian users of GPS and operates on only the L1 frequency with its lower rate C/A code. Military users operate in the Precise Positioning Service (PPS) which employs both the L1 and the L2 frequencies. Military users also have a cryptography code that permits selective access to the higher rate P code for anti-jam and anti-spoof capabilities. Only the accurate position and velocity data available in PPS is sufficient to safely fly at terrain following altitudes.

Spread spectrum signal processing is used to provide additional jamming² and interference protection, to allow multiple access³, and to reduce the effects of multipath signal reflections. An example of the spread spectrum jamming enhancement is depicted in Figure 4.9.

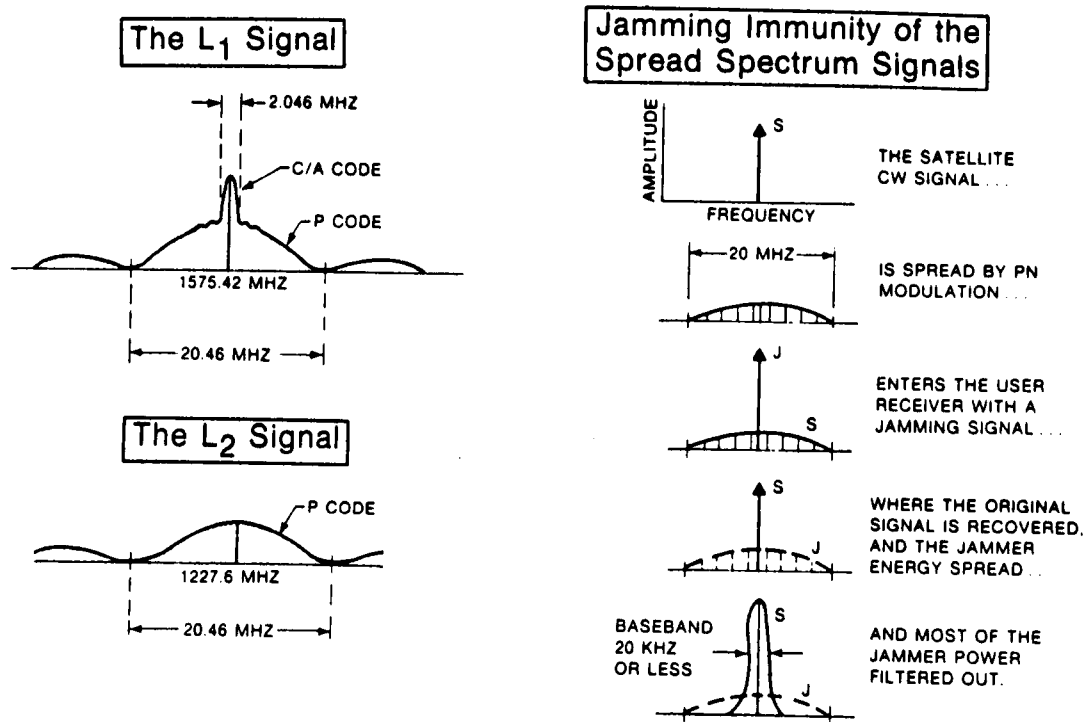


Figure 4.9. Spread Spectrum Signal Processing

Data messages are also transmitted on the carrier at a 50 bits per second rate. The data messages include the elements necessary for a GPS set to use the signals including satellite ephemerides, system time, satellite clock

² Spread-spectrum is not effective in the presence of (noise) wideband Gaussian jamming.

³ Single receiver is able to process multiple signals in frequency band and sort using doppler delays.

corrections, satellite health, and the critical C/A to P Hand Over Word (HOW). The GPS data message is presented in Appendix A, Figure 14.

GPS User Equipment Operation. The user's GPS antenna can acquire and track any visible SV signal and navigate with it or, based on operator input, may use stored satellite almanac data to select a specific visible SV. The GPS receiver conducts a two-dimensional search in the time and frequency spectrums to acquire and track the GPS signal. The receiver searches for the carrier's Doppler shift and the C/A code. A generic UE receiver operation is shown in Figure 4.10.

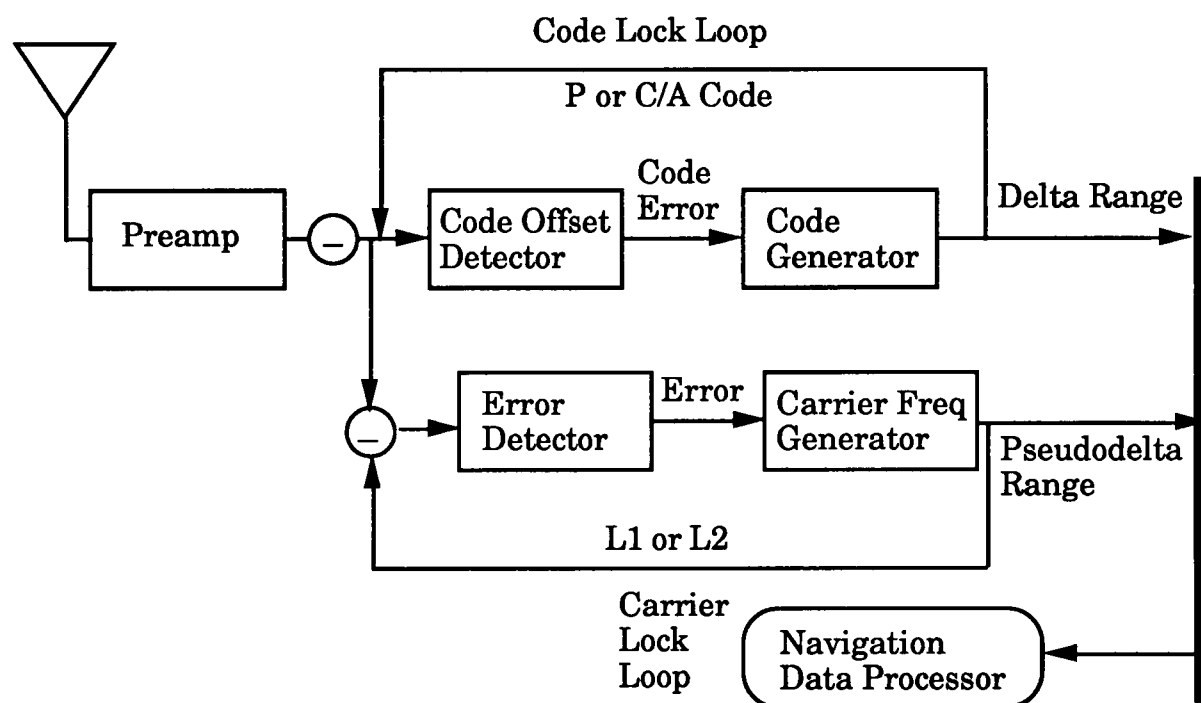


Figure 4.10. Generic Receiver Operation

After a C/A code track is acquired, the receiver/processor uses an autocorrelate algorithm to measure a time and calculate a Pseudo-Range (PR) from each satellite. A HOW from each satellite gives the user access to the P code tracking and permits transition to PPS performance from more accurate calculations of the PR. As shown in Figure 4-10, the UE also locks on to and uses the Doppler shift of the carrier to calculate vehicle velocity. A carrier tracking loop measures this second piece of data, the pseudodelta-range. The RP calculates the pseudodelta-range from the carrier phase shift over one second of time.

GPS System Performance Characteristics. SPS is inherently accurate to 30m, but in July of 1983 DoD announced that the horizontal position accuracy of SPS would be 100 meters 2DRMS. This degraded accuracy results from induced C/A code drift affecting the calculation of the pseudo-range. The method of degrading the system accuracy is classified and is regulated by the control segment. The "predictable accuracy" of the GPS system is a measure of accuracy of position with respect to an Earth coordinate system. This accuracy is normally measured in radial error as in Spherical Error Probable (SEP) or DRMS, the square root of the standard deviations of x and y errors ($\sqrt{\sigma_x^2 + \sigma_y^2}$). In GPS, 2DMRS $\approx 2.45 * CEP$, with a percentile probability of approximately 98.2% instead of the normal 95.5% for a 2σ CEP. The specified position and velocity accuracies for both services are shown in Table 4-11.

Table 4-10. GPS System Accuracy Specifications

Standard Positioning Service		Precise Positioning Service	
ACCURACY	INDICE	ACCURACY	INDICE
100 meter	2 DRMS (x,y)	16 meter	SEP (x,y,z)
150 meter	2 DRMS (z)	35 meter	2σ (x,y,z)
330 nsec	2σ (t)	100 nsec	2σ (t)
0.3 m/sec	2σ (v)	0.1 m/sec	2σ (v)

In operation, GPS is not as accurate as the theory. The position uncertainty a user experiences is a function of the geometric uncertainty resulting from the relative geometry of the satellites and the user. This dilution of precision, multiplied by the ranging error, is known as the Geometric Dilution Of Precision (GDOP). The closer the satellites are, the larger the GDOP. Figure 4.11 shows the breakdown of GDOP into its position and time components. PDOP is position dilution based on geometry, and is composed of horizontal (HDOP) and vertical (VDOP). Time (TDOP) is the range equivalent of clock bias.

If individual satellites are not specified by the user for navigation, the receiver/processor selects SVs for use by maximizing the volume of a tetrahedron formed by position lines from the user to the SVs. This method of selecting the usable satellites is a mathematical minimization of the effects of GDOP.

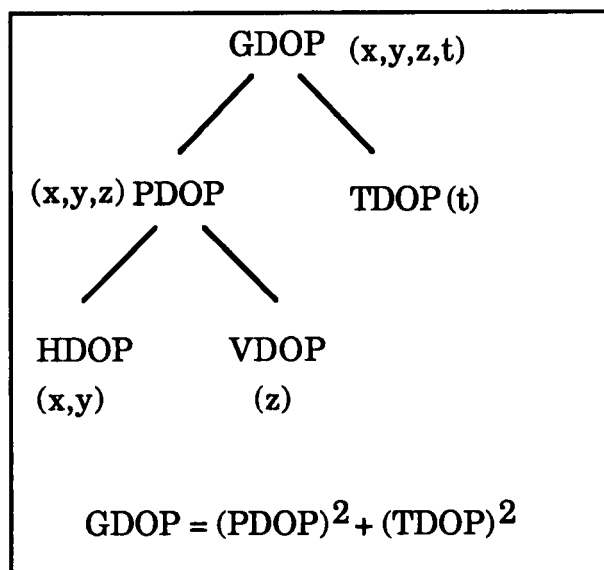


Figure 4.11. Types of Geometric Dilution of Precision

There are a number of error sources in each of the GPS segments that contribute to total system User Equivalent Range Error (UERE). As an example, the system accuracy can be described by Equation 4.7.

$$\text{RSS Position Error} \approx \text{PDOP} * \text{UERE} \quad (4.7)$$

Solving Equation 4.7 with a typical value of PDOP of 2.8 and a PPS system error responsibility of 5.3m, the RSS horizontal position error is 16 meters. Sixteen meters is the specified accuracy of PPS shown in Table 4-10. Table 4-11 describes the system error budget, identifies the contributing segment, and quantifies the error.

Table 4-11. GPS System Error Budget

GPS Segment	Error Sources	System Responsibility (1 σ m)
Space	SV Clock and Navigation Subsystem Stability	2.7
Space	Predictability of SV Perturbations	1.0
Control	Ephemeris Predictions and Model	2.5
Space	Other	0.5
Control	Ionospheric Delay Compensation	2.3
Control	Tropospheric Delay	2.0
Control	Other	0.5
User	Receiver Noise and Resolution	1.5
User	Multipath	1.2
User	Other	0.5
System UERE 1 σ = 5.3m		

Description of Errors. Clock Errors are short term clock errors are due to fractional frequency stability. They are modeled by typical Allan variances. One sigma errors for the two clock types are 1σ (1day) = $1 \cdot 10^{-13}$ for Cesium and $2 \cdot 10^{-13}$ for Rubidium. Long term instability is caused by drift in the atomic reference. There is also a small error induced by the clock error model itself.

SV Perturbation Errors are small errors that exist between the computed and actual satellite position calculated with the GPS ephemeris data. These errors are due to perturbation of the satellite in orbit.

An Ephemeris Error is an additional small error resulting from the equations used in the ephemeris prediction model and the actual implementation of the model.

With Atmospheric Errors , the speed of light is assumed to be constant in all measurement equations. Changes due to ionospheric and tropospheric signal delays are modeled as delay scaling factors (Equation 4.8).

$$PR = C * (\Delta t_{\text{meas}} - \Delta t_{\text{ai}}) \quad \text{with } \Delta t_{\text{ai}} = \Delta t_{\text{ion}} + \Delta t_{\text{trop}} \quad (4.8)$$

where

Δt_{ai} = Time delay due to atmospheric interference

Δt_{ion} = Time delay due to the ionosphere

Δt_{trop} = Time delay due to the troposphere

Ionospheric delays are caused by gas molecules in the ionosphere being ionized by ultraviolet radiation and producing free electrons. The effect on a radio signal delay is a function of the total number of free electrons per square meter along the path of the signal known as the Total Electron Content. This delay (Δt_{ion}) varies with time of the day, season, geographic location and solar cycle. Maximum signal disruption can account for as much as 40 meters error in calculated GPS position and can occur daily at 1400 local time, or seasonally in the spring or when located within ± 20 latitude of the equator. Ionospheric delays effect both pseudo-range (code delay) and pseudorange (phase advance) measurements. Ionospheric delay effects are removed by the GPS receiver using a eight coefficient, cosine fit, time-delay algorithm stored in the GPS almanac data.

Additionally, the use of dual frequency calculations compensate for the measured signal delays with real time processing.

Tropospheric effects result from the GPS signal passing through the unionized air of the troposphere and stratosphere. The signal is delayed due to the refractivity of the atmosphere (Δt_{trop}). A simple model incorporated in the UE, Equation 4.9, is used to describe and compensate for this delay.

$$C * \Delta t_{\text{trop}} = N_0 * H_s * e^{-ALT/H_s} * \text{COSEC } E \quad (4.9)$$

where

N_0 = Surface Refractivity 3.2 E-4

H_s = Troposphere Height 6900 m

E = Elevation

Receiver Noise Errors are pseudo-range errors induced by the code loop noise and are proportional to the code chip length. These errors are:

C/A Code $T_C = 293\text{m}$ therefore $1\sigma \text{ PR} = 11.1\text{m}$

P Code $T_C = 29.3\text{m}$ therefore $1\sigma \text{ PR} = 1.1\text{m}$

Pseudorange is affected by carrier loop noise but the error is the same for both codes.

A Multipath error results from the additional signal path length from a reflected signal. In the L band, reflection is normally rejected by the antenna gain pattern since circular polarized signals reverse upon reflection. Like receiver noise, the length of the chip and the reflected

signal power are the factors in the size of the error. The C/A code is responsible for a 12 meter error while the P code only accounts for only a 1.2 meter error. A quantitative rating of the GPS position accuracy is provided by the Figure of Merit (FOM). This value represents the position accuracy in meters and provides a rapid assessment of the operating performance of the GPS. The figure can be used by the aircrew to assist in the navigation mode selection or can be used by the system controller to weight the value of the GPS information. Typical FOM values are presented in Table 4-12.

Table 4-12. Figure Of Merit Values

Figure Of Merit (FOM)	Estimated Position Error
0	No Position Error
1	Less than 25 meters spherical error
2	Less than 50 meters spherical error
3	Less than 75 meters spherical error
4	Less than 100 meters spherical error
5	Less than 200 meters spherical error
6	Less than 500 meters spherical error
7	Less than 1000 meters spherical error
8	Less than 5000 meters spherical error
9	Greater than 5000 meters spherical error

These accuracies and errors will contribute to the overall operational capability of the system. Integration designs will require that these figures and their sources are completely understood and accounted for in the design of any passive terrain following system.

5. SYSTEM CONFIGURATION

Integration Options

Integration of GPS data into existing system architecture could take one of three forms depending on the level and type of GPS information used in the navigation solution. The stand-alone unaided receiver, while the least expensive and easiest to integrate, would incorporate the UE without modifying the host vehicles other than to adjust power supply and to create space for the components. The aircraft would use the the GPS data to correct navigation using manual entries to the existing system navigator in the MC. This approach would not work in the P³S since position and velocity data could not be usefully incorporate into the existing TF system.

The second method of integration would use the GPS UE as the prime navigator since it would calculate vehicle position with aiding data and GPS measurements. The receiver would be supplied aiding data, but no feedback to the aiding sensors would occur. This sensor-aided approach permits the existing velocity sensors, with minimum modifications, to improve performance during high vehicle dynamic periods and improve GPS system tracking of satellites in jamming conditions. The position solution could be passed to the mission computer, but the system navigator would still be GPS. Denial of the GPS signal for periods of time would degrade the navigation accuracy of the GPS and the host platform. Because the Tornado is highly maneuverable and could be flying in areas of high

electromagnetic jamming and interference, this method of integration is not desirable

The preferred approach, while most complex, is the fully integrated architecture. This method would use the GPS data as an additional sensor input to the system navigator which would generate navigation solutions and feedback aiding data to the GPS and other sensors. The existing subsystem interfaces would remain unchanged for the most part. The UE calculated position solution would still be produced, but would be utilized by the mission computer to calculate higher quality navigation solutions. The primary benefit of this strategy is the improved performance of all the systems and sensors with the added benefit of the GPS providing backup capability for the navigation computer. Figure 5.1 is a diagram of the general integration strategy for a fully integrated system.

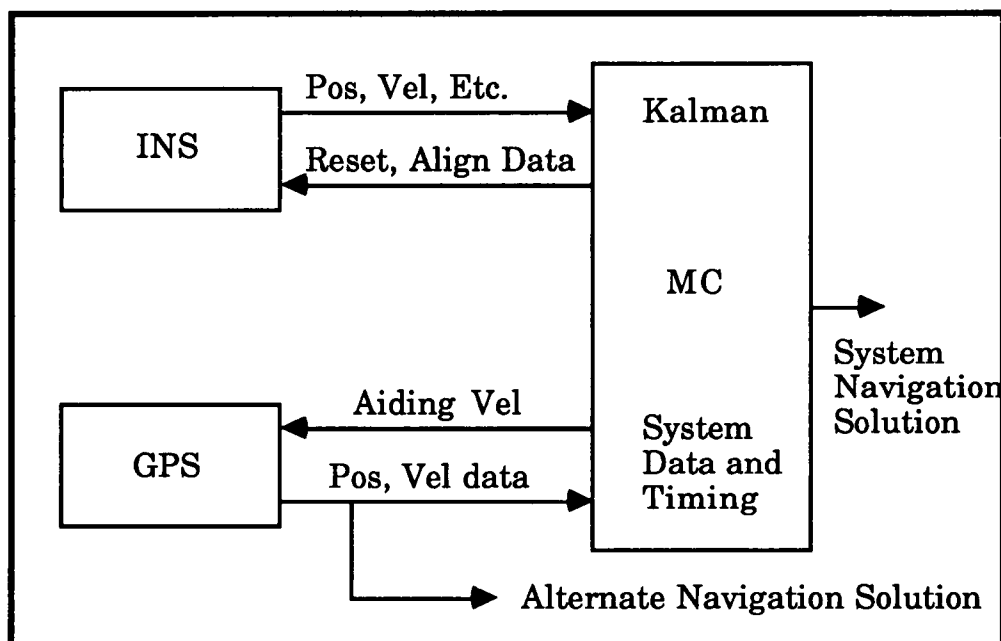


Figure 5.1. Diagram of Proposed Fully Integrated GPS UE

A disadvantage of this strategy is the regulation of time tagging mechanisms in the GPS and INS [17 Poor]. INS and GPS data must be time tagged and additional computations are required to interpolate Position and velocity data for data synchronization. This increases the complexity and throughput of the mission computer software and may cause data senescence caused by time tagging errors.

There are also two variations on the fully integrated system which differ in the values that are processed from the GPS and the the manner in which the data is processed. The direct integration approach uses the pseudo-range and delta range outputs, while the cascading approach relies on position and velocity outputs [18 Dayton]. The important characteristics of both approaches are shown in Table 5-1.

Table 5-1. Comparison of Direct versus Cascading Integration Strategies

Direct Integration	Cascading Integration
Uses Pseudorange and Delta Pseudorange	Uses position, velocity, and FOM
GPS provides code and carrier measurements to integration software	GPS provides navigation solution to integration software
Complete control of integration process	Time correlations from pre-filtering
Anomaly detection and correction easy	Anomaly detection more difficult
Can operate on less than complete constellation	Works poorly on reduced constellation
Easy to incorporate differential corrections	Differential corrections hard to handle
Requires more throughput	Requires less throughput
More complicated interfaces	Relatively simple interfaces
Antenna lever arm must be compensated for	No compensation required
Must estimate clock states	Poor GDOP hard to handle

While the direct integration process provides more complete control of the integration process and operates with less than a complete constellation, it is more complex, requires more complicated interfaces and data synchronization, and normally requires more computer throughput. Using the previously defined criteria, the final recommended mechanization is a cascading open-loop GPS/INS aided mechanization as shown in Figure 5.2

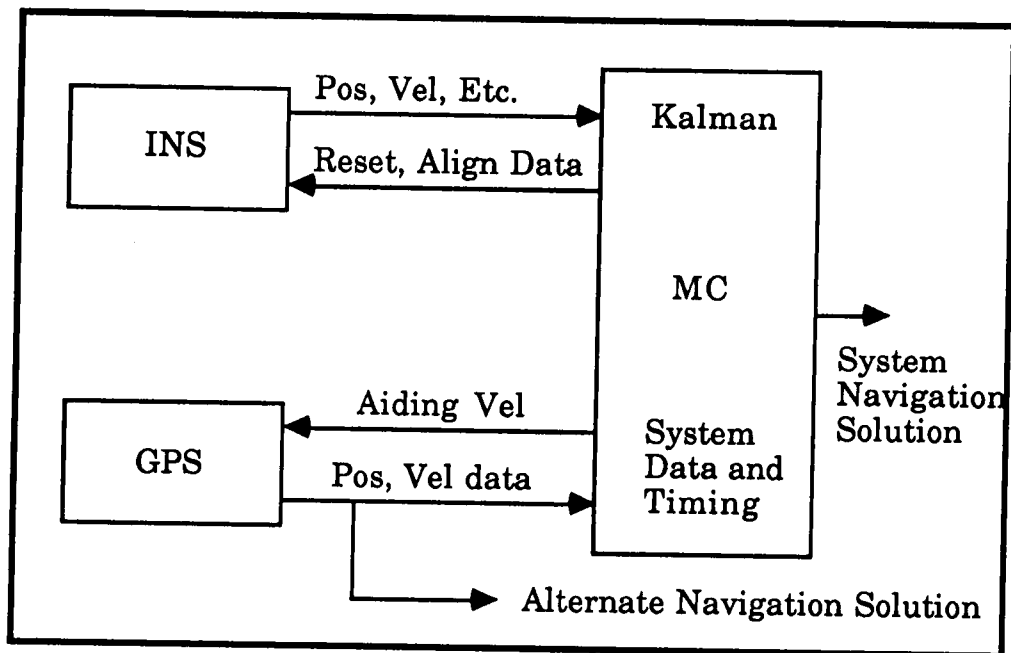


Figure 5.2. Cascading Closed-Loop GPS/INS Aided Configuration

A handicap of the cascading mechanization is the correlated position and velocity data from the use of two Kalman filters. A bad GDOP can cause the GPS system to diverge, with the INS following blindly. The Kalman filter experiences a very low variance and begins to weight GPS inputs heavily. The filter becomes overconfident and ignores the incoming information.

This closed loop divergence can be overcome by tuning or placing a lower threshold on the Kalman filter, by injecting noise into the system, and by thorough testing. One method of tuning the Kalman filter uses the FOM value to de-weight filter estimates. Also, since the recommended system uses calculated data as opposed to raw data, the system performs more poorly when there is not a complete constellation (4 or more SVS). During these times, the existing navigation system accuracy can be used for navigation and to speed reacquisition of satellites.

The aiding or periodic reset of the IN helps eliminate the characteristic long term horizontal and vertical drift. Too frequent resetting can contribute to closed-loop instability. Horizontal drift, although bounded by the 84 minute Scheuler feedback, benefits from aiding by helping remove Earth and gyroscopic rates. Vertical drift is unbounded and is affected by gravity and instrument errors. Unlike horizontal errors, vertical divergence continues to grow with time squared. Altitude aiding allows the barometric altimeter to be calibrated and used to replace GPS measurements for short time periods. Although reset rates are dependent on each integration scheme, a rate between 12 and 60 seconds is adequate to maintain accuracy. This rate also serves to mitigate data correlation, or aiding during velocity spikes. The FOM can also be used to alter reset rates when the GPS is degraded due to shadowing, maneuvering, or geometry.

P³S Hardware-to-Aircraft Interfaces

The Collins GPS User Equipment was the set selected for use in the Proposed Passive Penetration System (P³S). A simplified diagram of the system configuration is shown in Figure 5.3.

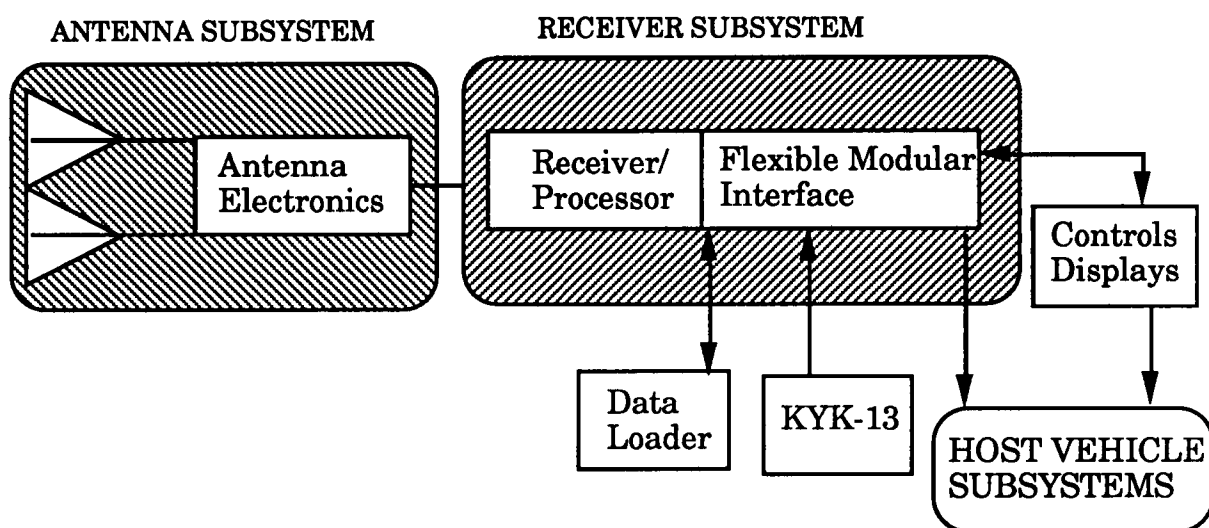


Figure 5.3. GPS UE System Architecture

The system consists of a conformal mounted Controlled Reception Pattern Antenna, a Fixed Reception Pattern Antenna (FRPA), Antenna Electronics, Receiver/Processor (R/P) subsystem, and a Data Loader. The top mounted controlled reception pattern antenna has a central reference element, with a 0 dBiC gain over a 160° beamwidth, surrounded by six auxiliary elements. The bottom mounted FRPA consists of two elements providing 0 dBiC gain from 5° to 25°. The FRPA increases antenna pattern coverage and reduces shadowing or loss of SVs during maneuvering flight.

Signals from both antennas are sent to the antenna electronics which uses null steering techniques to provide passive anti-jam signal reception.

The R/P subsystem contains the R/P connected to the flexible interface module. The flexible interface module contains all host vehicle unique hardware and software and permits manufacturing standardization on the R/P. The R/P contains five pseudo-range/pseudodelta-range channels for rapid SV acquisition and improved high dynamic performance. The channels input to a computer and microprocessors to handle signal processing, navigation and interface functions. Navigation data is processed in a 12-state Kalman filter, with position and velocity output in earth-centered-earth fixed reference coordinates. The UE set interfaces with the host vehicle through a digital MIL-STD-1553 A/B databus and can operate as an auxiliary navigator solving waypoint navigation, associated area navigation and can also coordinate transformation computations. A programmable data loader provides a method for the operator to load host vehicle and mission related parameters using 8K, 16-bit words. Since functional computations are performed by the R/P and interfaced over a digital Input/Output port, displayed parameters can be presented on the multifunction keyboard or display and do not require the additional space or weight for a unique GPS controls and display unit. An additional interface is supplied through a KYK-13 port where Selective Availability/Anti Spoofing (SA/AS) data can be loaded. GPS UE specifications and system performance parameters are presented in Appendix B, Table 4 and diagrams of the system components are shown in Appendix A, Figure 15.

P³S Component Placement

Based on an understanding of the components, the operation, and the capabilities of the proposed GPS and DTED passive terrain following system, the following section presents the recommended integration scheme. The proposed installation configuration of the five GPS UE components is shown in Figure 5.4.

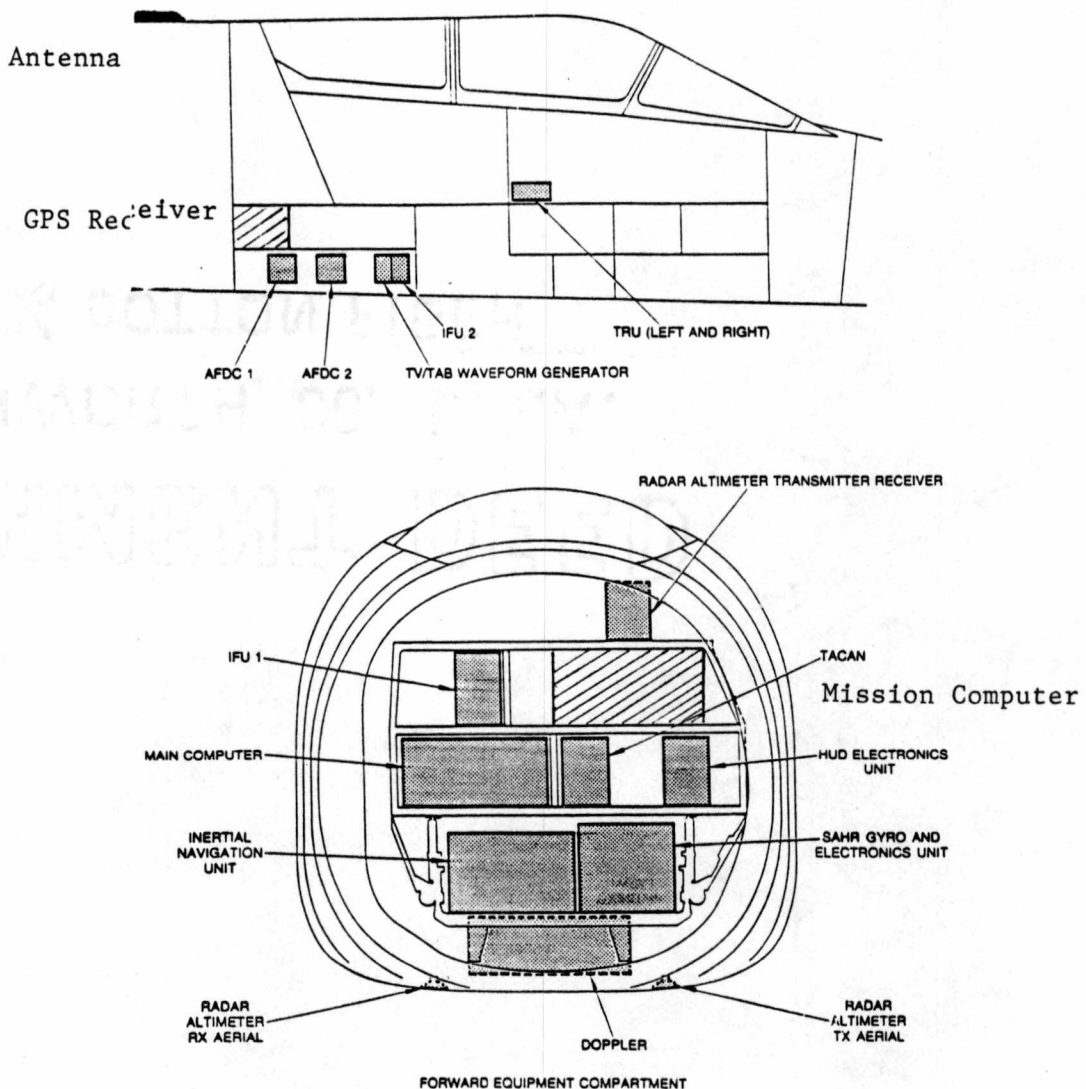


Figure 5.4. Proposed Location of P³S System Components

The placement of the 45 pounds of GPS components and the additional weight of a second mission components is based on the available avionics bay space and positioning the additional weight as close to the aircraft's center of gravity (cg) as possible to minimize flying quality changes. The potential problem of data signal latency, resulting from long wiring runs, is reduced by localizing the GPS components. Separation of the GPS set and the other major components of the navigation system (IN and MC) provides a vulnerability reduction through component redundancy and separation. The placement of the antenna subsystem closer to the aircraft's center of mass also shortens the antenna's lever arm reducing the antenna motion. This reduces the magnitude of the motion parameter that must be isolated from the GPS aiding and navigation equations [19 Gray].

The GPS UE operates on 115 V AC/400 Hz single phase power. Distributing the power supply to the proposed system's components allows full use of the redundant navigation capabilities. Loss of a generator or busbar No. 3 can affect only one of the two computers; in the event the GPS system is lost, the terrain following capabilities of the TFR are still available on busbar No. 1. The suggested AC power distribution is shown in Figure 5.5.

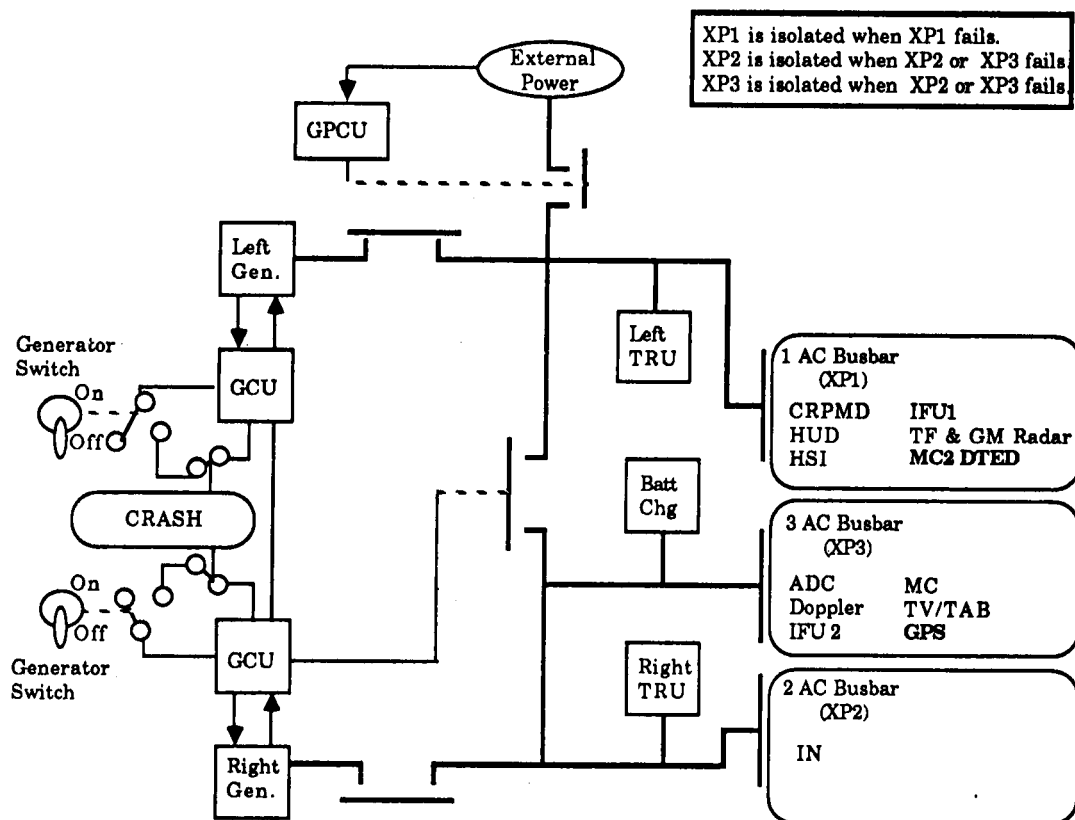


Figure 5.5. Simplified AC Power Distribution for P³S Components

Interface Requirements

Several interfaces are defined in the integration of the GPS UE in the Tornado. The first is the KYK-13/KOI-18 Interface which is used to allow entry of the SA/AS cryptographic keys. When power to the aircraft is off, the keys can be loaded and maintained by an internal UE battery. With power applied to the GPS receiver, the data may be also be entered through the data loader, control display, or the 1553 interfaces, permitting flexibility in the operational handling of classified materials.

The second and most important interface is the MIL-STD-1553 interface which provides access to all data from systems using the 1553 bus structure. The twisted pair, shielded cables use the standardized protocol and electrical characteristics to provide a high fidelity, fault tolerant interface.

A Baro-Altimeter interface permits direct communication between the pitot static system and the GPS to facilitate GPS aiding of the altimeter. Periodic calibration of the altimeter during periods of good GPS improves GPS performance when operating on less than four satellites. This function can also be carried out using the 1553 bus.

An additional interface is available and provides connections to load or transfer data to the GPS. The data loader interface allows loading of specific GPS navigation information. This interface can also be supplied by the 1553 bus.

A final interface with the system is available through the mission planning preparation station. This data includes GPS data in addition to other navigation and weapons delivery information. The use of a transfer unit, added to the Cassette Preparation Ground Station (Appendix A, Figure 16), would permit the transfer of standard DMA 1/2-inch magnetic tape to an additional mission cassette. However, due to the relatively small storage capacity of the cassette, limited geographic areas could be loaded onto the tape. This would constrain the airborne flexibility of the P³S by bounding the area where digital terrain data is available. To preclude this limit, and to permit future storage growth capacity, a CD reader is advised. The CD ROM interface for the loading of digital terrain and mission

planning data would be located in the aft cockpit, aft port bulkhead above the existing magnetic tape reader.

P3S Implementation Costs

The cost of implementing the passive terrain following system includes both hardware and software costs. Major hardware expenditures would include the GPS UE, the additional mission computer, the mission planning station and data transfer units. Software costs would result from the additional coding required for GPS integration, passive terrain following algorithms and rewrites to the OFP to handle integration and control of the new system. Table 5-2 depicts approximate figures for the major expenses incurred. Predictions of unit costs are unusable since a number of important variables are unknown. The major unknowns are the exact number of aircraft to be reworked, and the division of cost for software development. If individual countries operating the Tornado are responsible for software development the cost could be three times the cost if Panavia is the software developer and manager.

Table 5-2. Major Cost Contributors for P³S Implementation

Major Expense Components	Cost (Estimate)
Proposed CRPC UE Cost (FY 88)	66,400.00
Mission Planning System ¹	250,000.00
Digital Computer (MC2)	350,000.00
Data Transfer Unit	11,000.00
Software ²	2,000,000.00
Aircraft Rework and Modifications	750,000.00
Cost of Tornado	Unavailable

1. Three per squadron.

2. Total for development. Additional 15 - 20 million for software testing and validation

P³S Concept of Operations

The ground based automated mission planning system is a key element required to improve the operational effectiveness of the P³S. The computerized mission planning station would use the same digital database as the aircraft and would be used to plan navigation routes to the target. The system should include threat location databases as well as parametrics on the acquisition and targeting systems associate with each threat. Interactive software would select threat sights and display their fields of coverage as presented in Figure 5.6.

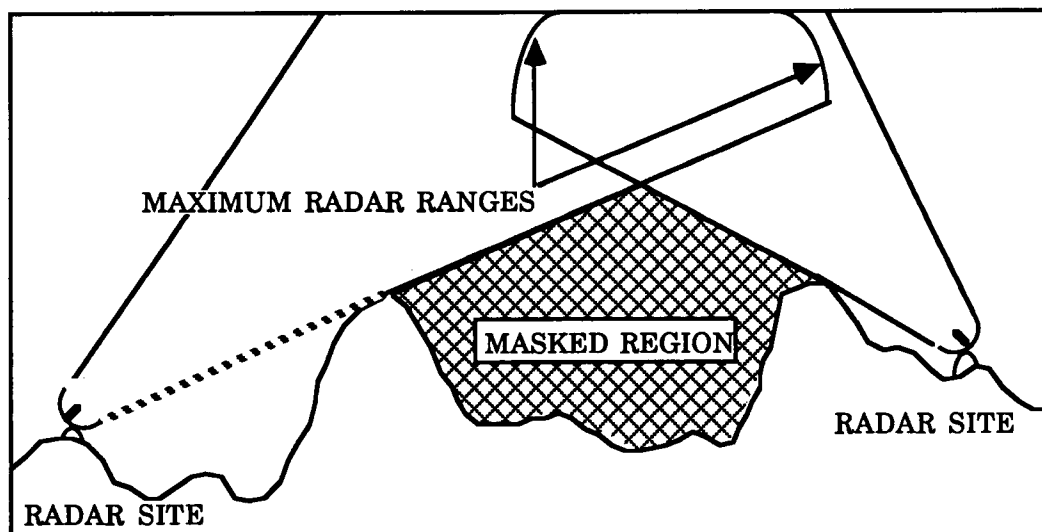


Figure 5.6. Sample Terrain Masking Calculation Made by Mission Planning System

The computer planner could use threat radar parametrics, site location, and terrain to develop radar terrain masking displays. These plots could be circumpolar presentations of line of sight estimations made every one to ten degrees as demonstrated in Figure 5.7.

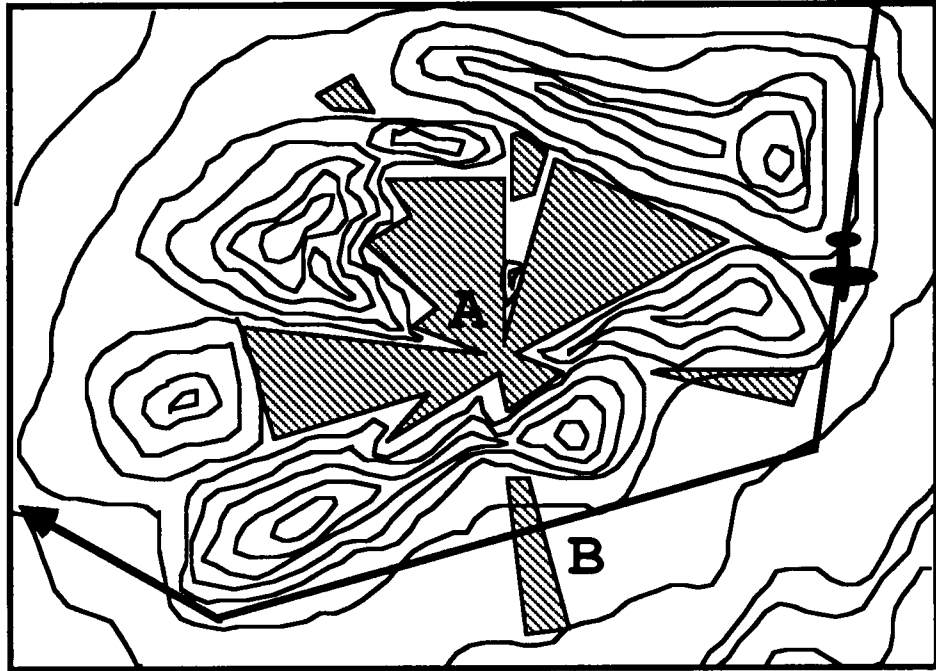


Figure 5.7. Sample Radar Terrain Masking Plot of a Typical Radar Site

The navigator could rapidly vary the target ingress altitudes to determine the best route and altitude options required to minimize threat exposure time [20 Huss]. The desired planned navigation route would include standard waypoint and fixpoint coordinates as well as altitude profiles to create a terrain following, threat avoidance route to the target. This initial route would take into account planned turns and anticipated aircraft performance to accurately define the Desired Flight Path (DFP). The route could be evaluated by a survivability subroutine which would determine if the threat had a clear line of sight for each point on the route, and if the aircraft was exposed, calculate a risk factor based on threat parameters. Multiple threats could be summed for each point and survivability estimates made for each route segment. The value of the survivability

estimate would only be as good as the apriori knowledge of known threat locations and would not include the capability of unknown or mobile threats. The highest priority threats could be highlighted allowing the navigator to change portions of the route to avoid critical threats.

Figure 5.8 demonstrates this technique. The navigator has selected a route which minimizes exposure to the single SAM threat located at point A. The route does not extend further south of the site because the survivability analysis indicates that the brief exposure at point B is insufficient for the SAM to detect, acquire and engage a target.

At the completion of the planning, the navigator would have used the computerized mission planner to generate a highly survivable (based on known threats only), three-dimensional terrain following path which minimizes the aircraft's threat exposure times. The Planned Flight Path (PFP) would be saved with other mission planning information on to the magnetic tape cassettes or CDs.

The aircraft MC2 would be the terrain following navigator in the passive mode. Software modules would construct a terrain following route in a similar fashion as the existing TFR. To minimize the human factors and training impact, the P³S would not have significant functional differences from active terrain following and would use the same display systems.

Figure 5.8 is a functional diagram of a proposed scheme for calculating the airborne terrain following flight path when operating in a passive mode.

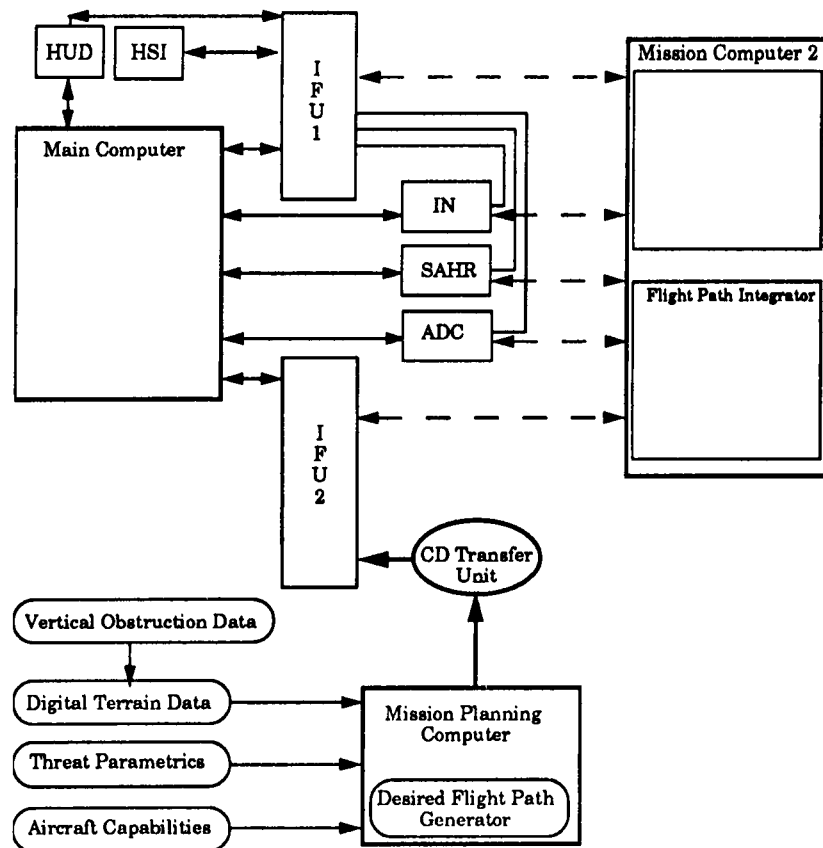


Figure 5.8. Functional Diagram of Proposed Software Modules for the P³S

The Flight Path Integration (FPI) module would be the controlling module responsible for evaluating aircraft position, flight parameters and operator inputs to generate correct steering to the planned route or the manual route entered by the navigator. A secondary function of the FPI would be monitoring performance of the P³S system and sensors to ensure safe operation. The FPI would monitor the navigation mode selection, the

steering mode (AFP or MFP), P³S system and sensor status to determine the navigation steering mode priorities. This is a redundant function normally assigned to the MC and would run as a background function until MC failure or engaging the P³S. In the passive mode, the MC2 would assume navigation control. The reason for the change is due to programming the MC2 to estimate and generate steering commands to rejoin the PFP after deviations for terrain or threat avoidance. The software would calculate a series of paths to fly the aircraft to intercept the PFP in the most direct route or at the next waypoint depending on navigation options selected by the navigator. The module would monitor the aircraft deviations from the PFP. If deviations were within software performance and safety limits the steering commands would be generated as described above. If deviations were large (i.e., new routing) the computer would also monitor the database accuracy and boundaries. If the computer determined the P³S was unable to perform due to loss of terrain data or poor data quality, the mode would switch to active TF if the TFR was available. If the TFR was not functioning or had been secured by the navigator, the computer would generate the standard fly up warnings and execute a safety fly-up. Satellite FOM, navigation data from other sensors, and flight data would also be monitored by the IFP. If navigation accuracy degraded, the IFP would program brief scheduled looks from the TFR to verify or update terrain profiles. The worse the navigation accuracy, the more frequent the active scans of the terrain would occur, up to a complete switch to active TFR in the event of loss of GPS for extended periods.

The Required Flight Path (RFP) interfaces with the IFP to generate actual required flight paths based on in flight parameters. Pitch angle, roll angle, ground speed, drift angle, course, and other aircraft flight data from the IN and various attitude and navigation sensors are stored in computer arrays including a height, vertical velocity, position, and acceleration arrays. This data is updated each time the RFP module calculates a new flight path.

The terrain profile data base is scanned and read into range bins from 2000 feet to 10NM, an additional 2 nm farther than the TFR scan. The additional two mile range is scanned for only two pieces of data. The first is any terrain feature that exceeds the current aircraft /P³S capabilities. The other piece of information looked for in the extended scan is the presence of a navigation turnpoint. If a waypoint is present, a coupling subroutine would ensure terrain clearance in the turn and maximize turn performance to:

1. remain on the IFP
2. initiate an early or late turn to maximize radar masking from the closest, highest priority, preflight planned threat in the data base
3. climb at the turn point based on preflight planning and inflight parameters

Each time the terrain profile is scanned, a discrete, merged flight profile is generated which consists of the new terrain and aircraft parameters merged with updated terrain and sensor data. The algorithm, constrained by aircraft performance limits, ride setting and set terrain clearance, attempt to construct a flighty profile that meets the following objectives:

1. Satisfy minimum terrain clearance height.
2. Easily followed profile for manual terrain following, and consistent with limiting parameters and aircraft capabilities.
3. Smoothed for noisy terrain and profile-to-profile discontinuities.
4. Remain within 5% of the set clearance altitude

The RFP calculates two passes through the terrain data each time a new profile is constructed. Based on aircraft flight data and maximum terrain in each range bin, critical points are established. The critical point is that point where the profile has been modified because the required aircraft maneuver or performance exceeded the set limits. In other words, critical points are the earliest points where a flight maneuver is started in order to remain within system design limits. The two passes, which look at the close and far side of terrain obstacles, are blended to create a single flight path. These segments could then be joined using a similar algorithm to blend the end points of the segments within the specified ride limits. Variable accelerations would then be applied to the entire flight profile to desensitize the profile to terrain noise, smoothing the ride quality. The arrays then describe the flight path as a series of points, defined by an altitude, vertical velocity and an acceleration. In a final step, the system would calculate a series of connecting points to join the previous RFP and the newly calculated one, allowing delays for aircraft response times. An example of how the module would process information to create a flight path is presented in Figure 5.9.

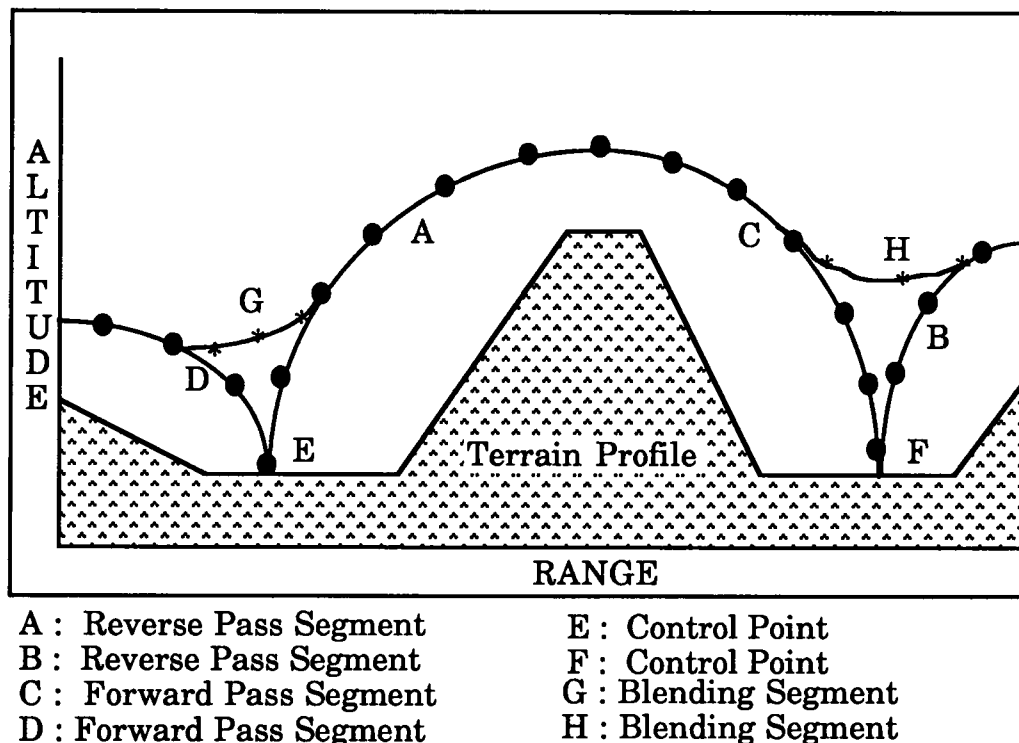


Figure 5.9. P³S Flight Path Generation

The final module translates the RFP vertical acceleration commands and feedback from the aircraft's present state conditions into CSAS inputs and steering commands. System limits are applied, and inputs from the coupling algorithm are used to ensure adequate clearance during maneuvers. While not limited by the TFR hardware limits, a series of software limits will need to be applied to make the aircraft states predictable for the algorithms. Excessive dynamic maneuvering would still cause the system to revert to manual pilot control.

6. PASSIVE TERRAIN FOLLOWING SYSTEM SIMULATION AND EVALUATION

Simulation Plan and Philosophy

To help assess the feasibility and quantify the low altitude capabilities of the proposed terrain following system, a simple computer program was written. The FORTRAN program (Appendix C) flies a simulated aircraft over digital terrain data and determines the frequency of impacts of a safety bubble and the actual aircraft with the terrain. The flight path generator used operator inputs to look ahead of the aircraft to critical points in the terrain data and calculate TF commands. The TF command generator was not an attempt to reflect the actual or proposed algorithms required to maintain TF flight profiles. Rather, it provided a mechanism to move the simulated aircraft through the route segment to evaluate the affects of total system errors on the system performance capabilities. Because of the low fidelity of the simulation, specific P³S integration issues were not addressed.

The results were used to assist with an initial subjective assessment of the P³S's feasibility. Since the existing TFR algorithms have been used safely during the life of the Tornado, a demonstration of similar low altitude passive TF capabilities would indicate the potential feasibility of the enhancement and would suggest the need for flight testing. Using the total errors of all major components of the P³S, the model attempted to determine a safety standard, the minimum altitude the system might be

safely flown. This safety estimate was based on a probability of successful mission completion without impacting the terrain.

Simulation Description

The input page of the simulation allowed the operator to enter the flight conditions desired for each run as presented in Figure 6.1.

ENTER THE STARTING ALTITUDE(ft) FOR THIS SCENARIO:

	RIDE SETTING	DESIRED MAXIMUM PUSH OVER COMMAND	DESIRED MAXIMUM PULL UP COMMAND
1	HARD	+0.05g	+3g
2	MED	+0.25g	+2g
3	SOFT	+0.50g	+1.5g

SELECT THE NUMBER ASSOCIATED WITH THE DESIRED RIDE SETTING:

ENTER THE STARTING VELOCITY(knots) FOR THIS SCENARIO:

GPS FIGURE OF MERIT VALUES

FOM	ESTIMATED POSITION ERROR
0	No position error
1	Less than 25 meters spherical error
2	Less than 50 meters spherical error
3	Less than 75 meters spherical error
4	Less than 100 meters spherical error
5	Less than 200 meters spherical error
6	Less than 500 meters spherical error
7	Less than 1000 meters spherical error
8	Less than 5000 meters spherical error
9	Greater than 5000 meters spherical error

ENTER THE ESTIMATED FOM :

Figure 6.1. Input Page for P³S Simulation

The input files analyzed are summarized in Table 6-1. These variables are the same parameters selected by aircrew during actual TF operations, including the aircraft clearance height, ride setting, and aircraft velocity. A fourth variable was selected to reflect an average GPS degradation value to be used during the flight profile. Terrain matrices containing sample digital terrain data were used to create four route segments of varied terrain ruggedness. The data was similar in quality and format to Level 1 DTED. The aircraft, modeled by a sphere with a 15-foot radius, was flown at low altitudes over the terrain following segments.

To represent the horizontal uncertainties of the DTED database and the horizontal GPS error component, three adjacent paths of digital terrain data were used. A subroutine, which interpolated linearly between adjacent elevation data measurements and base on the GPS degradation figure entered, selected a path to the left or right of the actual center reference path as shown in Figure 6.2.

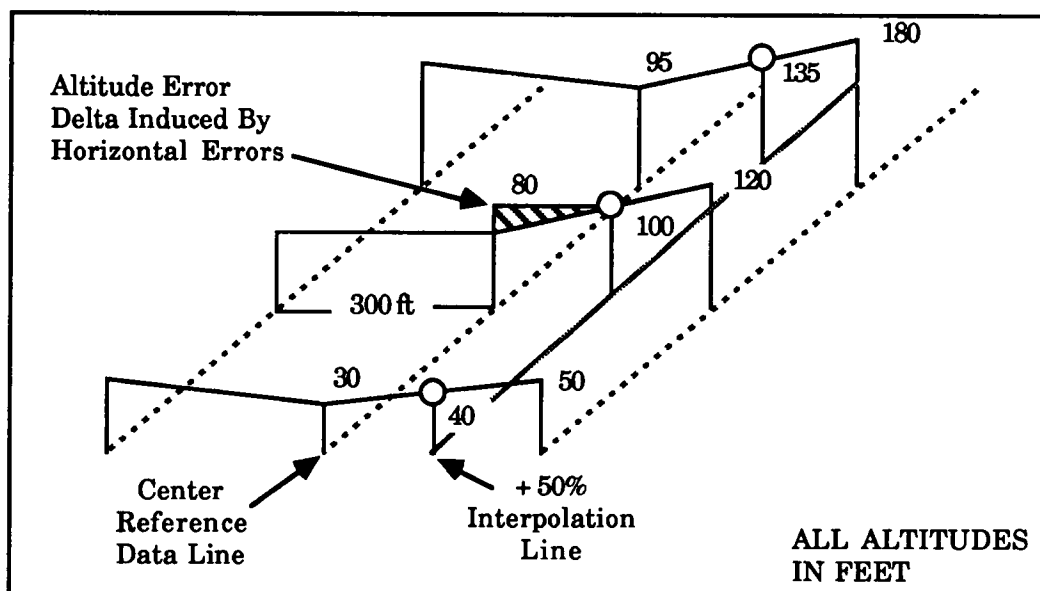


Figure 6.2. Terrain Interpolation and Horizontal Position Errors

The aircraft was then flown over the selected offset route; however, terrain following commands were based on the terrain data for the center of the route, creating an artificial horizontal error. To assist in conceptualizing the route of flight and sample terrain ruggedness, two computer-generated views of route terrain, viewed from a 500-foot aircraft perspective, are presented in Appendix A, Figures 18 and 19.

Vertical terrain errors were modeled separately using a routine that randomly varied the vertical measurement errors within ± 30 meters of the specified digitized data accuracy requirement. Combined, the vertical routine and the horizontal shift routine approximately represented the specified DTED system errors.

Vertical GPS errors were induced using a separate subroutine. This subroutine was an upper level simulation of system errors and did not

attempt to model the individual error components of GPS. Because the GPS system accuracies are monitored and displayed as a FOM, the maximum error level for a run was set by selecting a FOM value. Additionally, because the proposed system design incorporates a supplemental use of the TFR based on poor FOM values, or system navigation inaccuracies, maximum GPS errors were bounded at 100m in the simulation. Assuming aircrew monitoring of the P³S during terrain following flight and the use of aircraft sensors to update position, the 100m limit was considered operationally realistic and used as a safe operating criteria.

A series of 216 runs were made over each of the four terrain route segment for a total of 864 simulated passive terrain following segments. The runs were divided by altitudes, where clearance height was held constant and velocity and GPS accuracies were allowed to vary within the programmed limits (Appendix C).

Following each run, flight statistics were stored in the Run Output File for analysis. A file element included the run number, selected parameter values, number of safety bubble impacts (a sphere of radius 50 feet), aircraft impacts and the locations of the impacts. These values could be examined in a tabular format as depicted in Appendix D, Table 1. A sample graphic showing pictorial descriptions of two of the runs is shown in Figure 6.3.

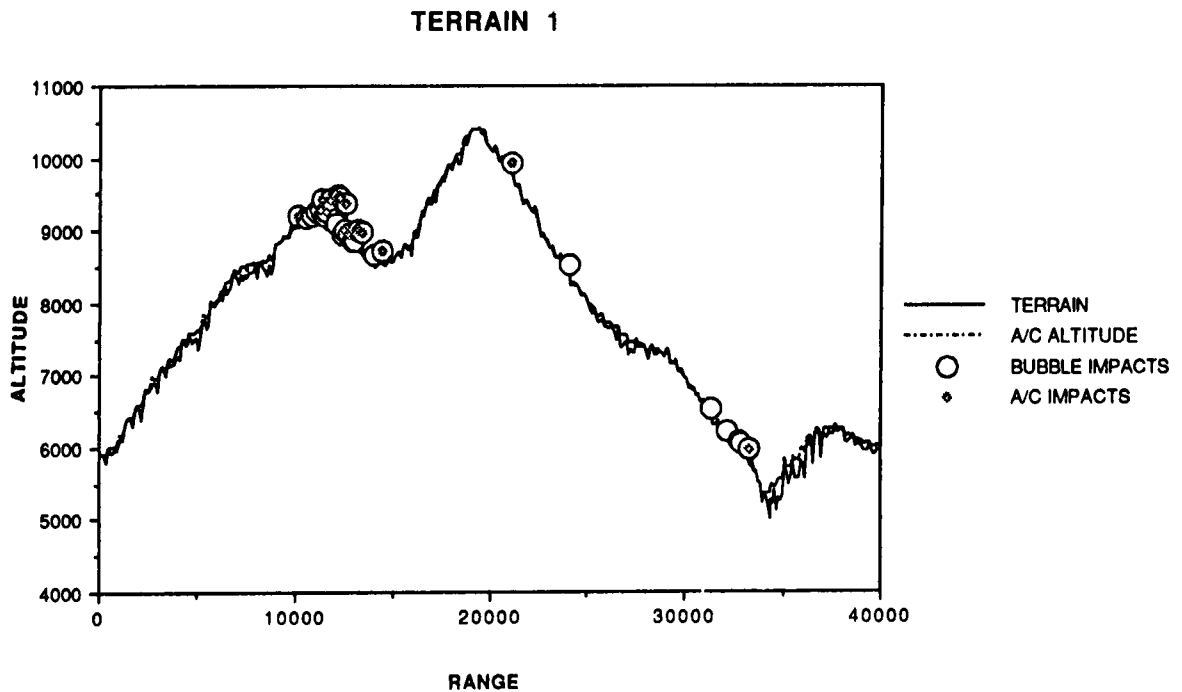


Figure 6.3. Sample P³S Simulation Run Depicting Terrain Following Flight Path and Aircraft Impacts

The second subroutine was used to calculate statistics based on the results of the runs. The routine Run Output File was sorted by parameter and the means and standard deviations for the selected elements of the file were calculated.

Simulation Analysis

Table 6-1 is an impact summary for all of the 864 simulation runs.

Table 6-1. Impact Summary of 864 Simulation Runs

Terrain Number	Ride Setting	Bubble Impacts	Aircraft Impacts	Number of Runs	Bubble/Aircraft Impact Ratio	Impact/Run
1	1	178	77	72	2.31	1.10
1	2	84	35	73	2.40	0.48
1	3	33	10	71	3.30	0.13
		Σ 295	Σ 122	Σ 216		0.57
2	1	6	2	72	3.00	0.03
2	2	4	0	73	N/A	0.00
2	3	0	0	71	N/A	0.00
		Σ 10	Σ 2	Σ 216		0.01
3	1	162	98	72	1.65	1.36
3	2	100	53	73	1.89	0.73
3	3	39	24	71	1.63	0.33
		Σ 301	Σ 175	Σ 216		0.81
4	1	11	5	72	2.20	0.07
4	2	1	1	73	1.00	0.01
4	3	3	1	71	3.00	0.01
		Σ 15	Σ 7	Σ 216		0.03

Review of graphic examples presented in Figure 6.3 indicates that the plots of the digital terrain are extremely noisy. This factor and the relatively simplistic flight algorithm may contribute a large percentage of false impacts. A large number of simulation induced impacts could be removed by incorporating the actual control algorithms and employing an interpolating, terrain smoothing routine.

Table 6-2 is a summary of impacts for all runs over the terrain segment one. It depicts a correlation between the accuracy of the aircraft position relative to the ground and the number of impacts for a given flight

altitude. It also shows an overall impact sensitivity to ride setting, and as could be anticipated intuitively, the more dynamic "Hard" ride setting appear to increase the likelihood of impact 2:1 over "Medium" and 5:1 over "Soft" settings.

Table 6-2. Impacts versus Terrain Following Altitude for Terrain Segment One

Number of Impacts (Bubble/Aircraft)					
FOM	Altitude	200	300	400	500
0		0/0	0/0	0/0	0/0
1		0/0	0/0	0/0	0/0
2		4/0	0/0	0/0	0/0
3		43/16	0/0	0/0	0/0
4		248/102	12/4	0/0	0/0

Assuming an 500NM mission range, the simulations involved a flight of approximately 3,240NM or 6.5 times the operational mission range. The minimum safe altitude was established as that altitude where the probability of 1 terrain clobber per 850NM mission was less than 1:100,000. Analysis of data from other terrain segments shows that there were a total of 30 impacts in 864 runs that occurred at the 300-foot flight altitude. Twenty-seven of those impacts occurred when the FOM was 4 and the remaining three impacts took place when the FOM value was 3. Given GPS accuracies within 75 meters (represented by a FOM of 3), the system can

operate safely within a minimum safe altitude band between 300 and 400 feet AGL. From this data, the probability of an impact while flying at 400 feet was 0.000925%. This initial analysis indicates that the system can adequately parallel the safety and performance standards of radar TF systems. With increased navigation accuracies limits or the use of periodic active position updates, the system could safely operate at still lower altitudes matching the 200 to 300 foot operating range of the existing TF system.

7. CONCLUSIONS AND RECOMMENDATIONS

Conclusions

The Proposed Passive Penetration System appears to meet the designed goal to provide a complementary, non-radiating, terrain following capability for the Tornado aircraft. The use of GPS with its encrypted and coded signals, and jam resistant antennas will permit system operation in the European, high density, hostile electromagnetic theater. The terrain data base permits operation over any type of terrain and is not degraded overwater for naval employment. Loss of GPS satellites or extremely high power, large area signal jamming may degrade the system, but if required, the high accuracy of the existing navigation system and the capability to downgrade to active radar TF will provide an adequate back-up system. The system is also capable of operating for extended periods with infrequent GPS updates. The P³S provides a 24-hour, all weather capability and can be moded to offer optimized threat avoidance flight paths through terrain following flight.

The simulation of the system indicates that the system may not be able to safely operate at the absolute minimum altitude of a radar terrain following system, but it should safely operate within 100-200 feet of the 200-foot minimum radar TF altitude. This slight increase in minimum altitude could be offset by intelligent, threat avoidance routing planned to minimize exposure times to known threats. Additionally, when engagement by threat systems requires minimum altitudes to defeat

missiles or other weapons, the radar can be employed since the aircraft has already been detected and targeted.

This analysis also suggests that the system can operate over the entire flight regime of the current radar terrain following. Some existing roll-and-turn maneuver limits for the radar TF system will not apply to the proposed system, and because of the predictive nature of the P³S, the system may be able to operate in a larger dynamic envelop. Existing software and hardware is maintained and the additional required equipment is separated within the aircraft to provide further redundancy and improved survivability.

Both major components of the system, GPS and digital terrain data, have been tested and are in use in a number of other systems. Mission planning systems are currently available, further reducing already minimal technical risk. Much of the terrain following software is in place and would require minimal modifications to change inputs and create safety and performance tracking routines. From the simulations, DTED level 1 quality terrain data seems to provide sufficient accuracy and granularity to sustain safe terrain following flight.

The P³S would be completely internal and would not result in the loss of a pylon station to carry a pod. The minimum additional system weight and the slightly increased drag from the GPS antennas should cause only minor changes to the speed, range and handling characteristics of the aircraft.

Moreover, the synergistic benefits of incorporating the system would greatly outweigh any slight performance or handling changes. The system would offer an accurate navigation interface for intelligent weapons

permitting standoff targeting and handoff to a weapon, with the aircraft remaining well clear of the target threat area. Navigation, sensor pointing and target tracking are more accurate since the GPS supplies aiding information to the other aircraft sensors. The improved position information can also be used in intelligence gathering and reconnaissance to provide more accurate target coordinates. Future integration plans could take advantage of the existing GPS and threat avoidance capabilities to design Low Probability of Intercept algorithms for normal operation of both the TFR and the GMR. Further enhancements could include the use of passive night vision devices including FLIRs and Night Vision Goggles to enhance the safety and performance of the P³S.

Finally, the system is cost effective, maximizing the system gains for dollars spent. This susceptibility enhancement would reduce a sophisticated enemy systems capability to detect, track and engage the Tornado. Aircraft losses when operating against an IADS would remain at acceptable levels and additional assets would not be required to make up for increased aircraft attrition. The incorporation of the system also provides the groundwork for integration of smart stand-off weapons which could further improve aircraft survivability. Even when operating in lower threat scenarios, the enhancement improves the navigation and position accuracy of the Tornado making it a more accurate delivery weapon delivery platform. This accuracy equates to fewer missions and less ordnance required to destroy a target, or more cost effective platforms.

Recommendations

The successful outcome of this assessment suggests further testing to include additional simulation and flight test. The simulation should concentrate on the performance of the actual flight control programs as well as man-in-the-loop simulations to evaluate human factors. In particular, attention should be paid to the displays, warnings and cautions used to monitor the performance of the P³S and to the ways the aircrew distinguish between similar active and passive TF displays. During this subsequent modeling, heavy emphasis should be placed on safety aspects including testing of the new navigation Kalman states, graceful system degradation, and defining the actual probability of impact figures that would be used to evaluate the system. A sensitivity analysis should be conducted to confirm initial assessments of important flight parameters.

Flight tests should focus on the system performance in all types of terrains and flight envelopes. The mission planning system should be used to plan all terrain following flights to ensure accurate data transfer as well as checking the capability of the system to plan aircraft flight paths. Special emphasis should be placed on the system performance during degraded GPS acquisition and during high dynamic flight conditions. Finally, with the improved position and velocity inputs, flight tests should re-examine weapon delivery accuracies and adjust ballistics algorithms to improve the Tornado's bombing CEP.

LIST OF REFERENCES

LIST OF REFERENCES

1. Ball, Robert E. The Fundamentals of Aircraft Combat Survivability Analysis and Design. American Institute of Aeronautics and Astronautics, Inc. New York, New York.
2. Course notes from "Aircraft Design, Aviation Systems 510" Presented by Dr. U. Peter Solies, University Of Tennessee.
3. Scanlan, John W. II Phase II-A Developmental Testing of the Tornado Gr Mk 1 Airplane. United States Naval Test Pilot School, November, 1987.
4. Baird, Charles A. Performance Analysis Of Elevation Map Referenced Navigation Systems. Fifth IEEE/AIAA Digital Avionics Systems Conference, 31 October-3 November 1983.
5. Christense, Kurt K. A Covert Radar Scan Control Algorithm. Eighth IEEE/AIAA Digital Avionics Systems Conference, 27 October-1 November 1987.
6. Huss, R. E. and Weber, J. W. Route Finding Using Digital Terrain Data. Fifth IEEE/AIAA Digital Avionics Systems Conference, 31 October-3 November 1983.
7. AP 101-4101-15A, Tornado GR Mk 1 Aircrew Manual. August 1980.
8. AER. 1F-PA200-1, Tornado Aircraft Flight Manual. 1 November 1985, Change 4. 15 April 1987.
9. AER. 1F-PA200-1A, Tornado Aircraft Flight Manual Performance Data. 15 March 1982.

10. Canada, John R. and Sullivan, William G. Economic and Mutiattribute Evaluation of Advanced Manufacturing Systems. Prentice Hall. Englewood Cliffs, New Jersey.
11. Hudak, G. J. Strategies for Optimizing GPS Capabilities in Host Vehicle Integrations. Institute of Navigation Conference, January 1988.
12. Skolnik, M.I. Introduction to Radar Systems, Second Edition. McGraw-Hill, New York 1980.
13. Hoisington, David B. Low-Probability-of-Detection Radar Designs Challenge Tactical ESM Capabilities. The International Countermeasures Handbook, 11th Edition, 1986, EW Communications, Inc. Palo Alto, CA.
14. Digitizing The Future. Second Edition, The Defense Mapping Agency, Washington D.C., October 1989.
15. Bjornsen, G. L. and Price, D. M. NAVSTAR GPS System and User Equipment Description. Flanders Technology International Fair, March 1985.
16. Course notes from "GPS Executive Overview; Principles, Program and Applications." Presented by Keith D McDonald, Navigation Technology Seminars, Inc.
17. Private communication on GPS with Mr. Walter Poor, Center for Naval Analysis, Washington. DC, 27 June 1990.
18. Dayton, Ronald A. and Nielson, John T., A Flight Test Comparison of Two GPS/INS Integration Approaches.
19. Gray D. E. and Krishnamurti G. Features and Capabilities of the DoD GPS Receivers for Aircraft and Seaborne Applications. Paper presented at Space Division, Institute of Navigation, September 1987.

20. Huss, R.E. and Weber, J. W., Route Finding Using Digital Terrain Data. Fifth IEEE/AIAA Digital Avionics Systems Conference, 31 October-3 November 1983.

21. Denton, Richard V. and Jones, J. E. Optimal TF/TA Route Planning Using Digital Terrain Elevation Data. Fifth IEEE/AIAA Digital Avionics Systems Conference, 31 October-3 November 1983.

ADDITIONAL REFERENCES

22. Strong, Gilbert. Introduction To Applied Mathematics. Wellesley-Cambridge Press, Wellesley MA 1986.

23. Guide To Preparation of Theses and Dissertations. Sixth Edition. Knoxville Tennessee: The Graduate School The University of Tennessee, 1985.

24. NAVSTAR Global Positioning System (GPS) Security Classification Guide. Los Angeles California: Headquarters Space Division Air Force Systems Command, 23 July 1984.

25. Blank, R. W. and Rhodes, W. D. Jr. Field Test Results Prove GPS Performance Utility. Position Location and Navigation Symposium, 4-7 November 1986.

26. Brandtberg, Hans Integrated Electronic Map System. Fifth IEEE/AIAA Digital Avionics Systems Conference, 31 October-3 November 1983.

27. Shackelford, Mark D. Global Positioning System (GPS). USAF Fighter Weapons Review, Spring 1985.

APPENDICES

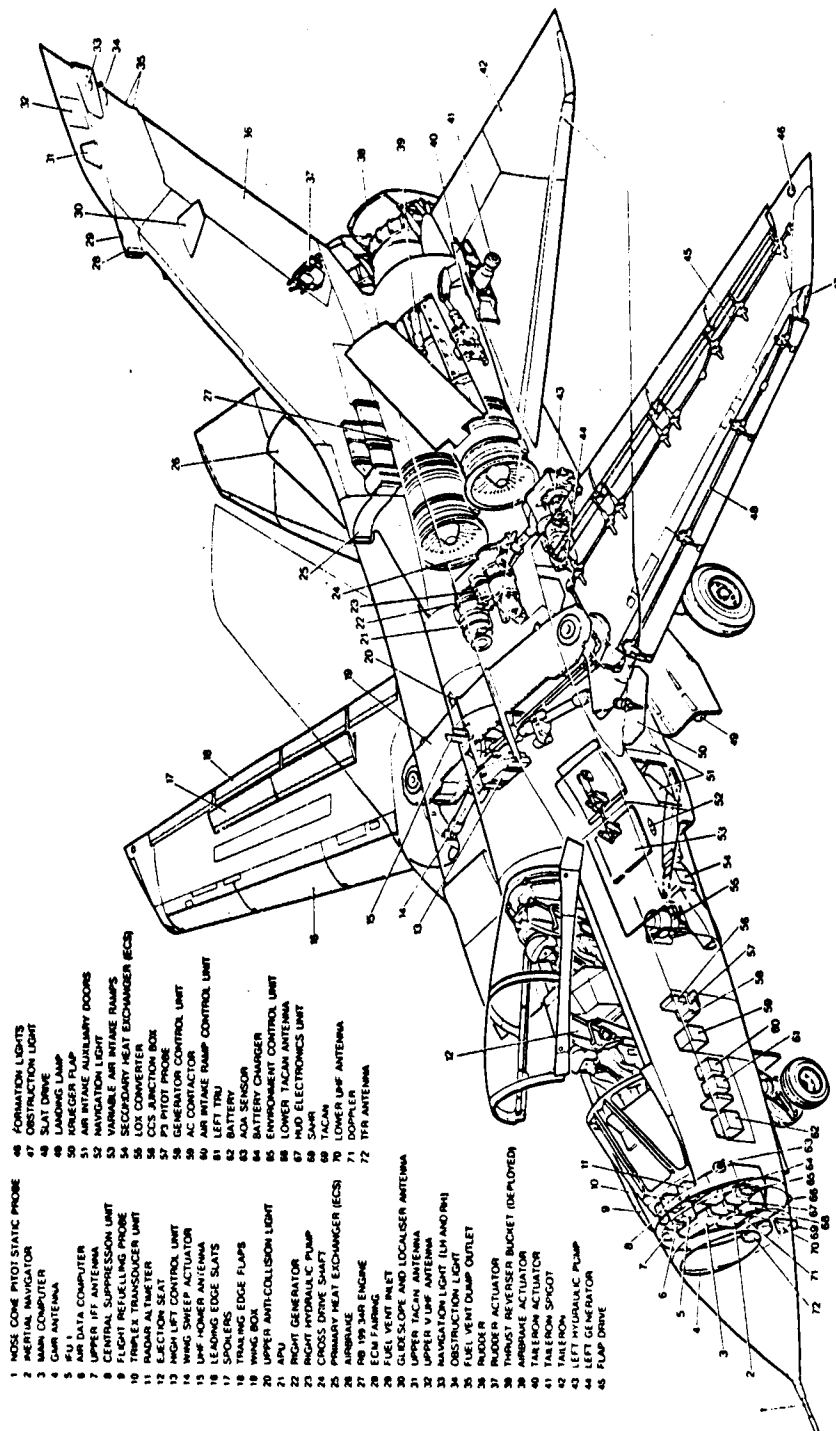


Figure A-1. Cutaway View of Tornado Aircraft

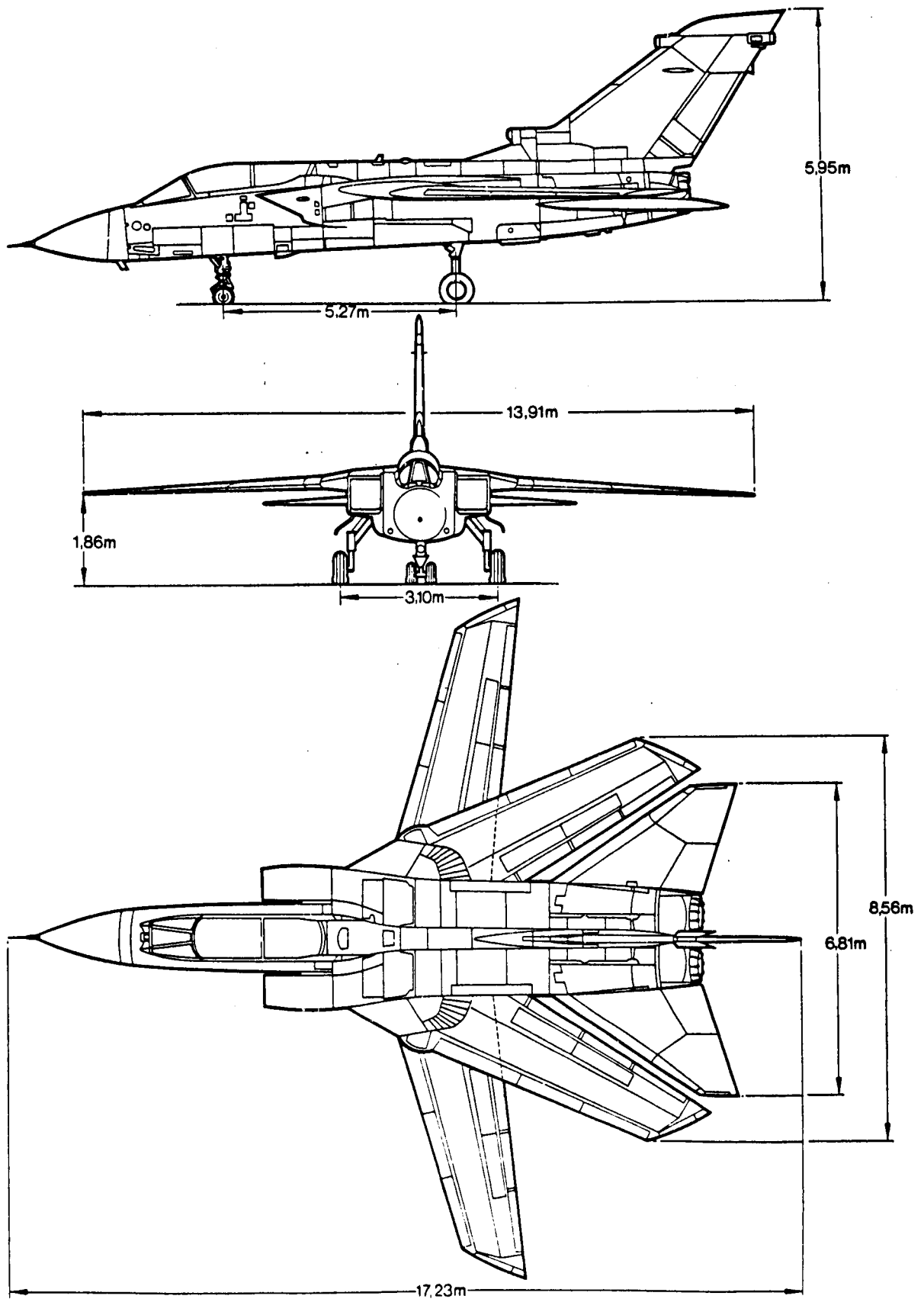


Figure A-2. 3-Dimensional View of the Tornado Aircraft

REAR COCKPIT (STRIKE)

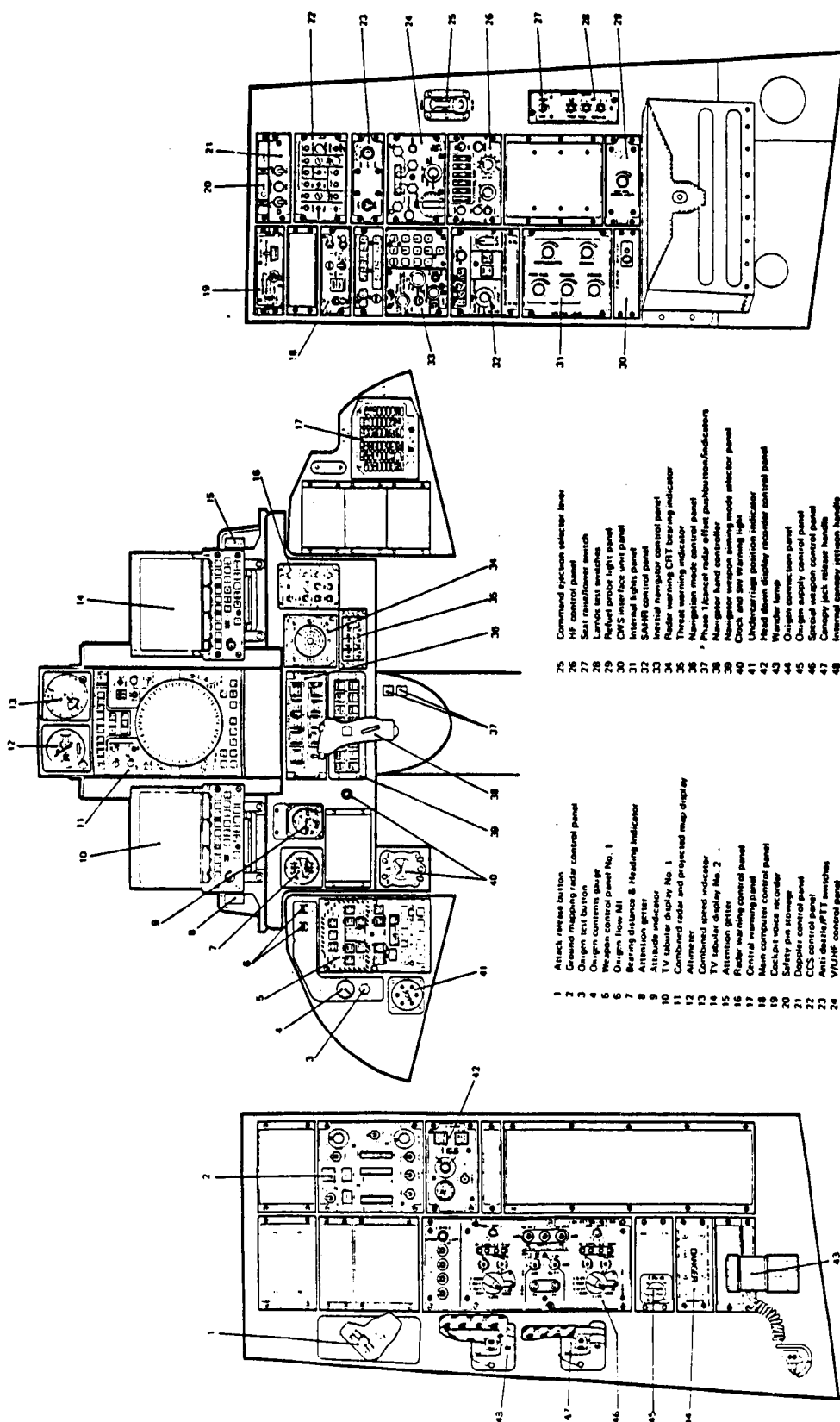


Figure A-3. View of Tornado Aircraft's Aft Cockpit

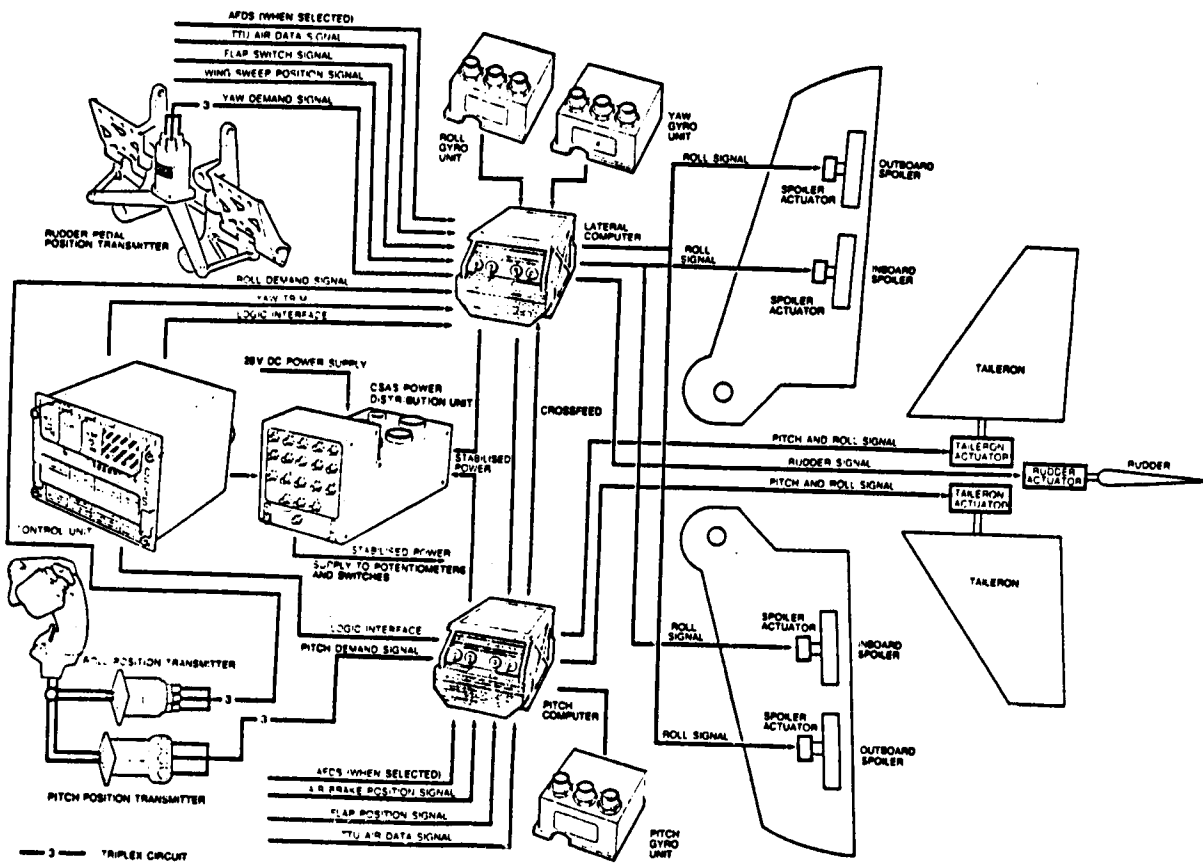


Figure A-4. Diagram of Tornado Flight Controls

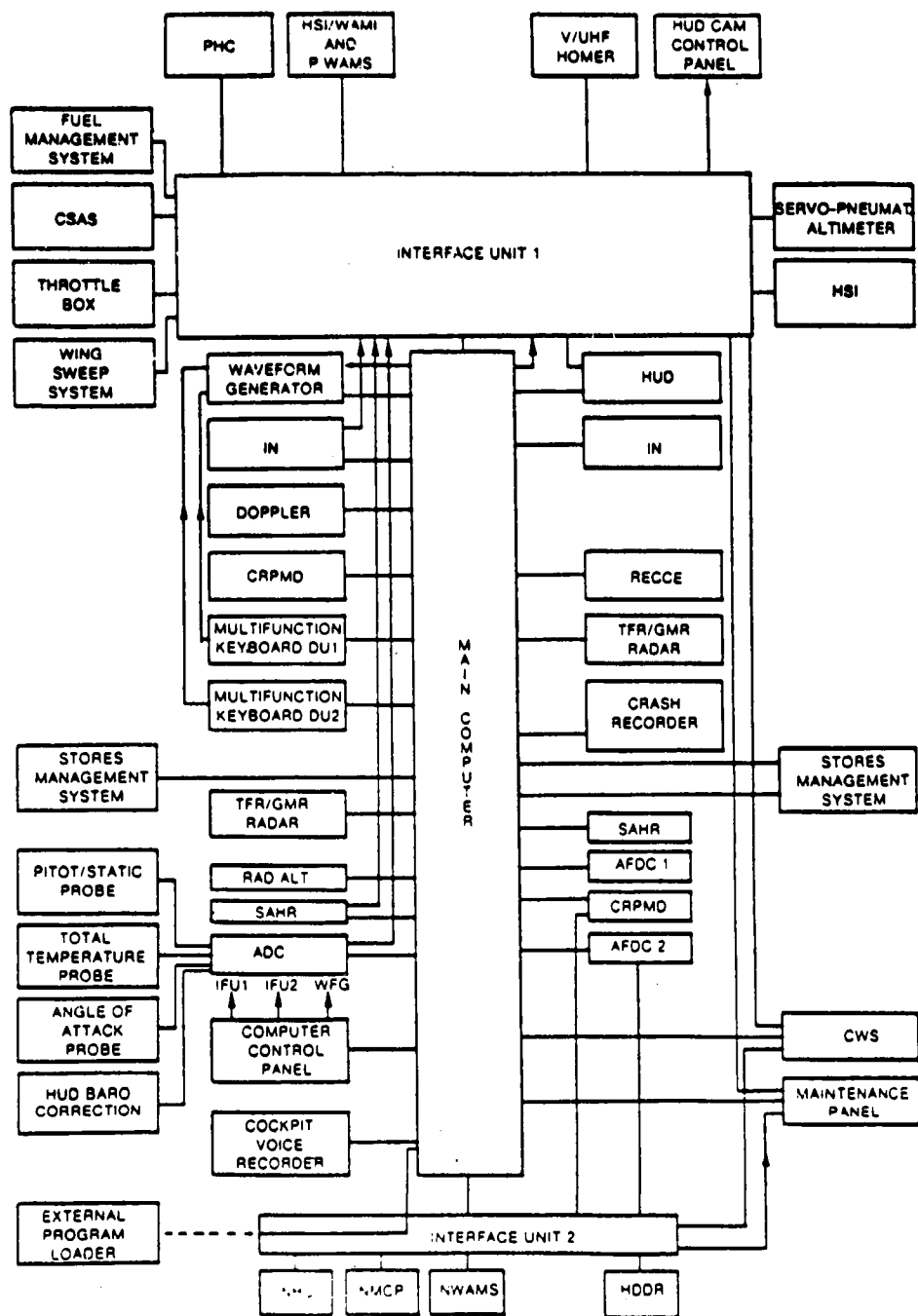


Figure A-5. Mission Computer Format

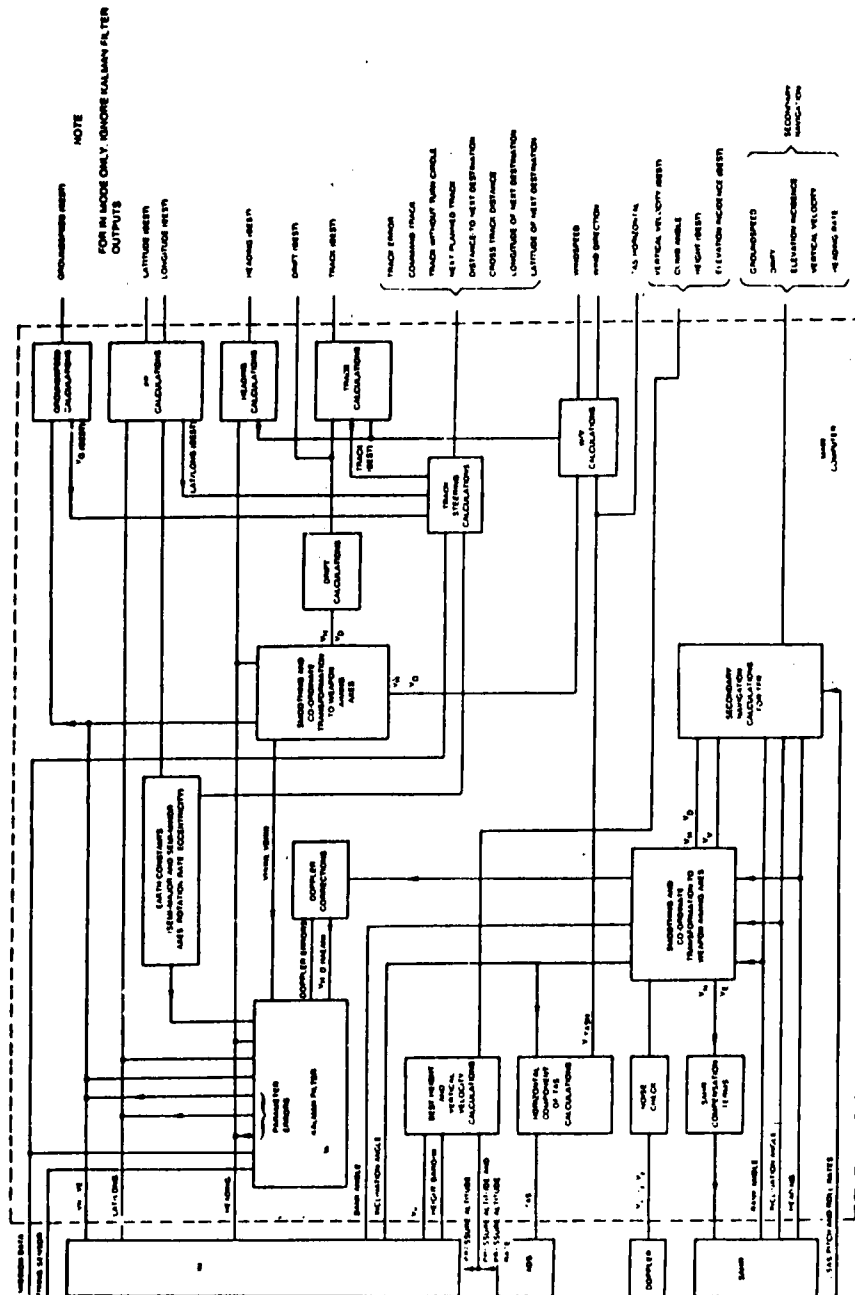


Figure A-6. Inertial Navigator Inputs and Outputs

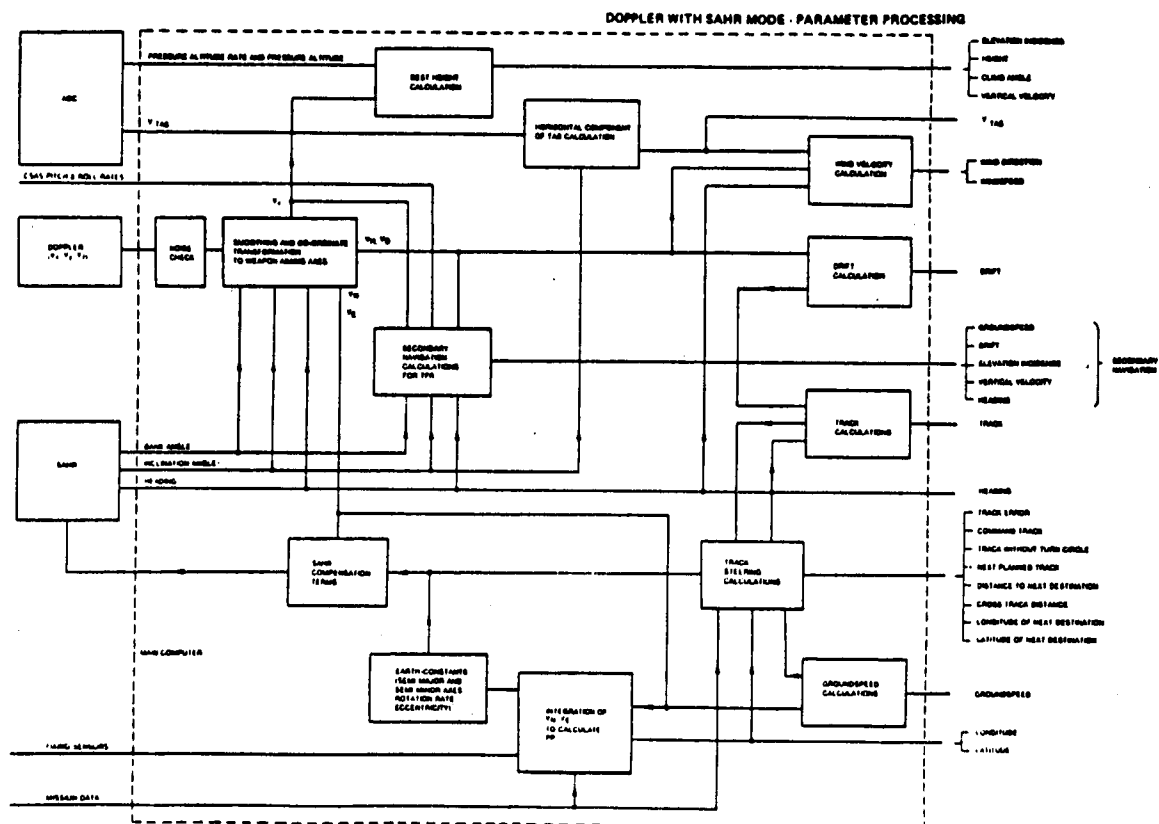
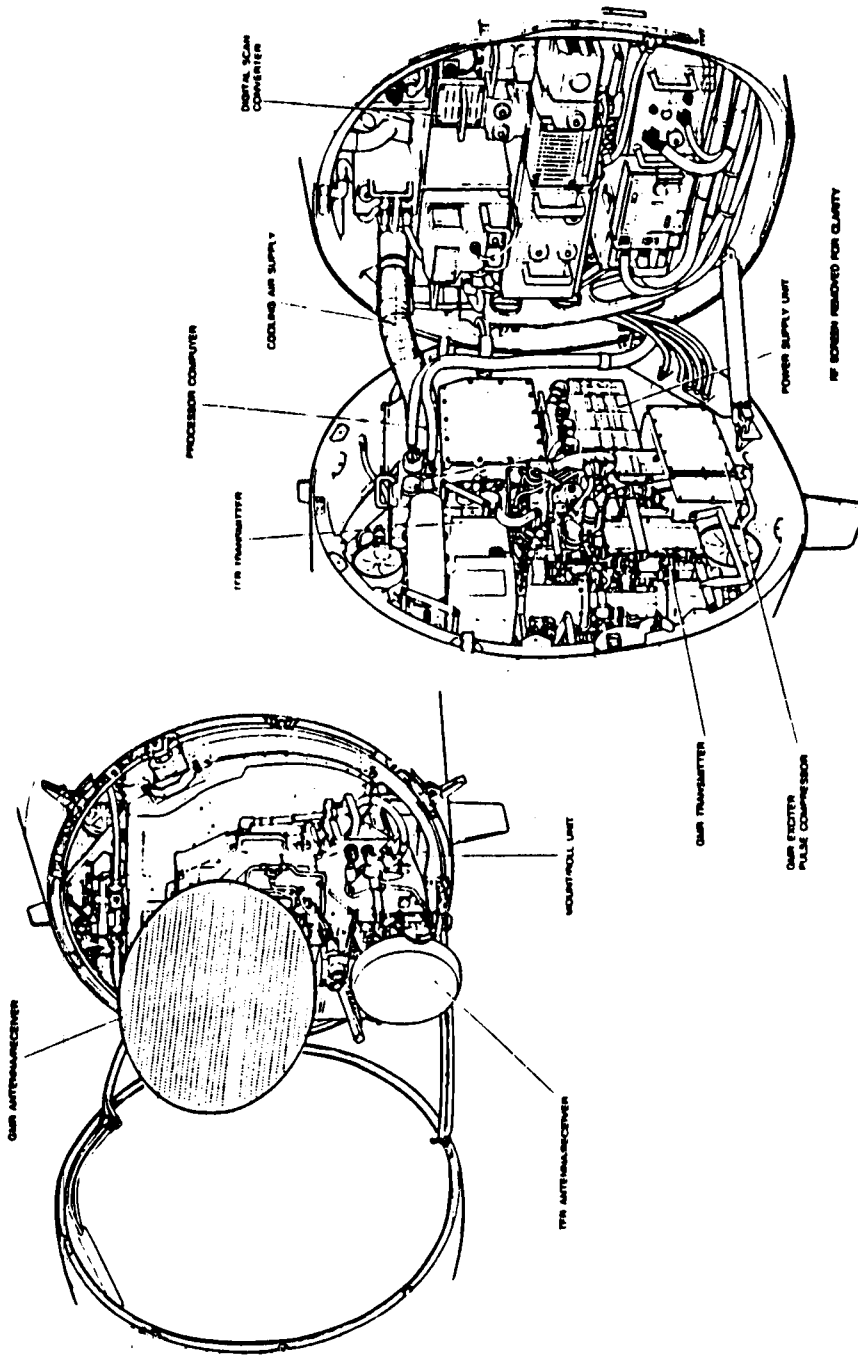


Figure A-7. Navigation System Flow Diagram for the Doppler and SAHR Mode



TFR: Terrain Following Radar

GMR: Ground Mapping Radar

Figure A-8. Terrain Following Radar Component Locations

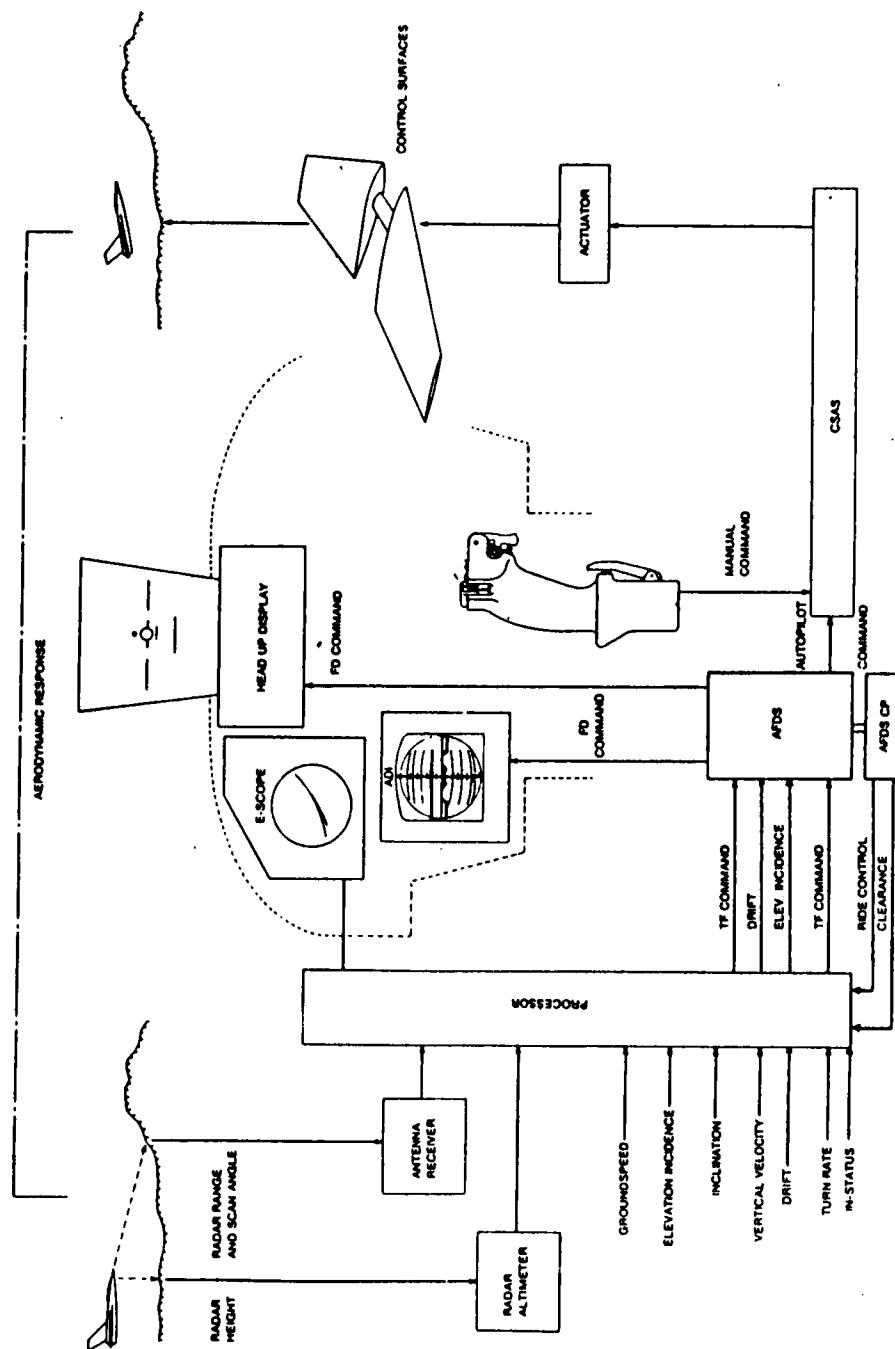
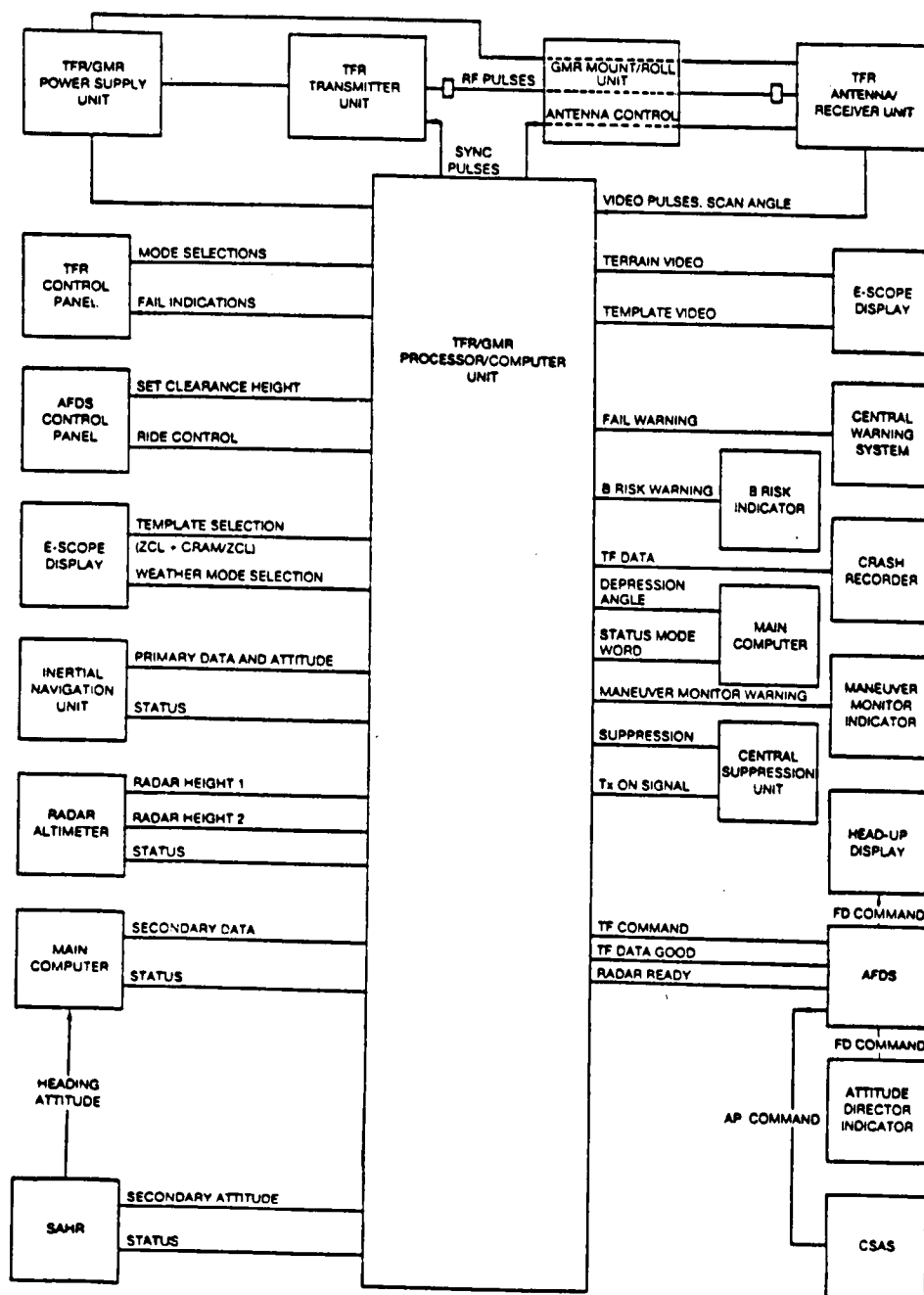


Figure A-9. TFR Vertical Steering Commands and Displays



TFR: Terrain Following Radar
 GMR: Ground Mapping Radar
 ZCL: Zero Command Line

AFDS: Autopilot and Flight Director System
 CSAS: Command and Stability Augmentation System
 CRAM: Clearance Range Ahead Monitor

Figure A-11. Terrain Following Radar System Block Diagram

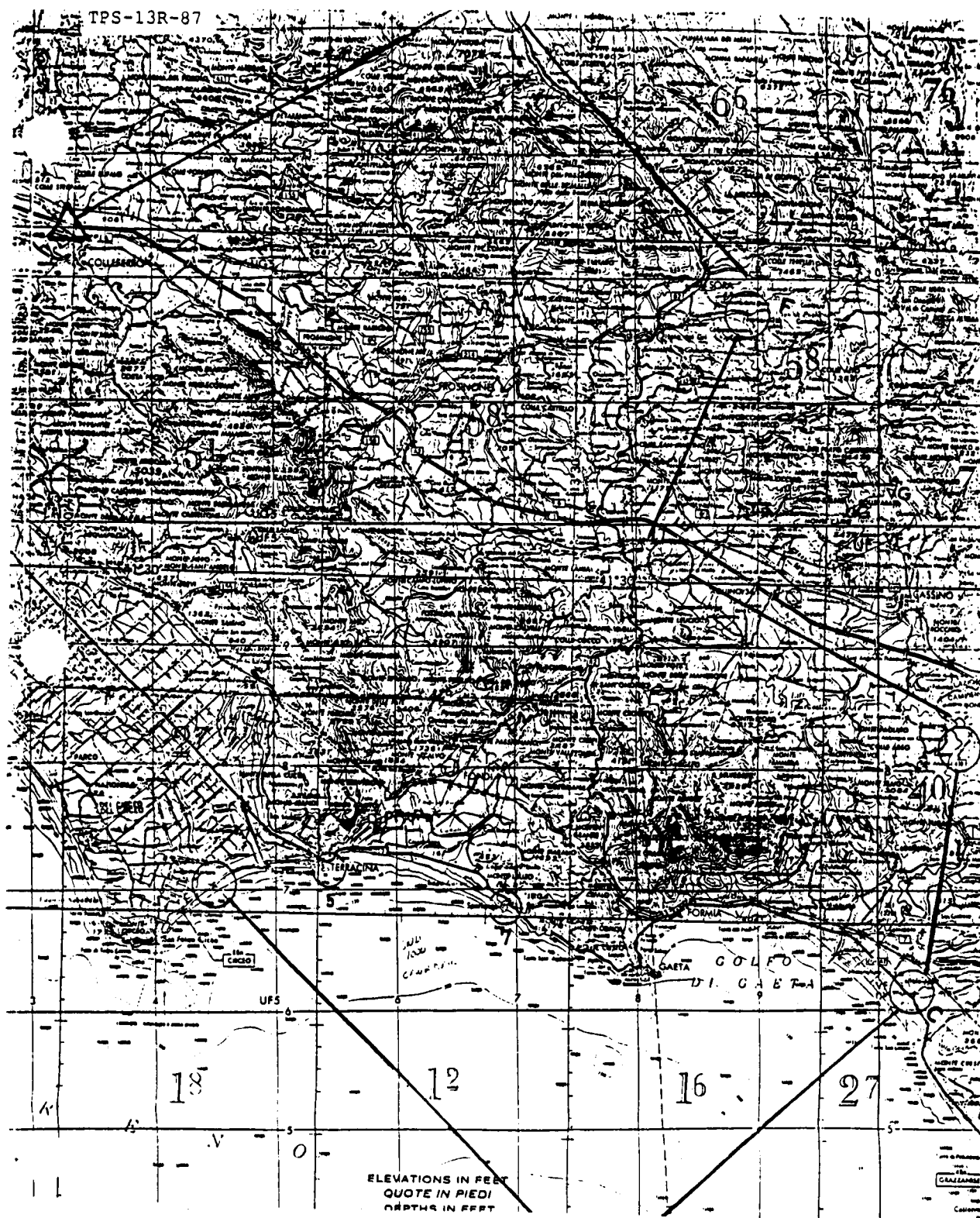


Figure A-12. Terrain Following Route One

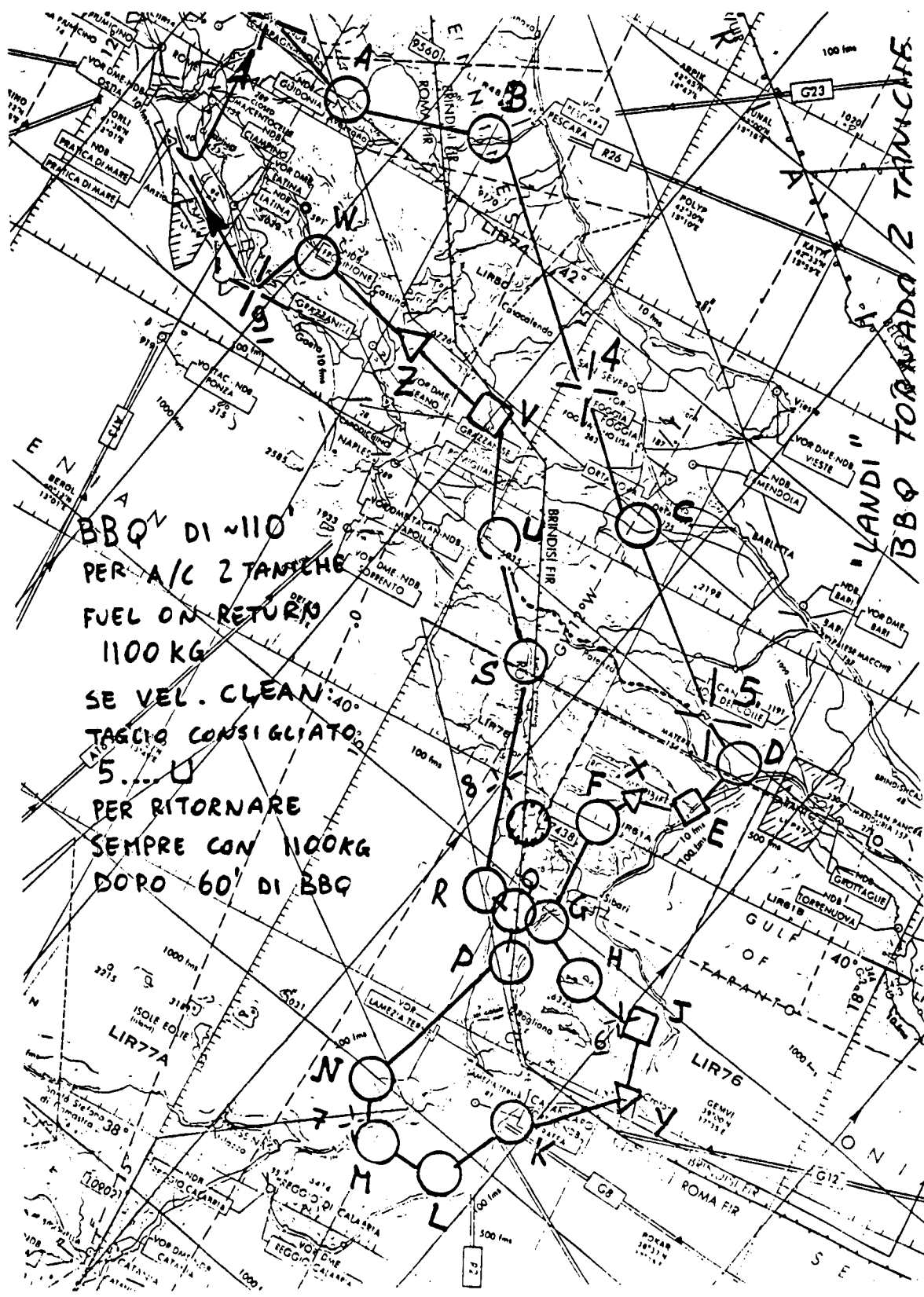
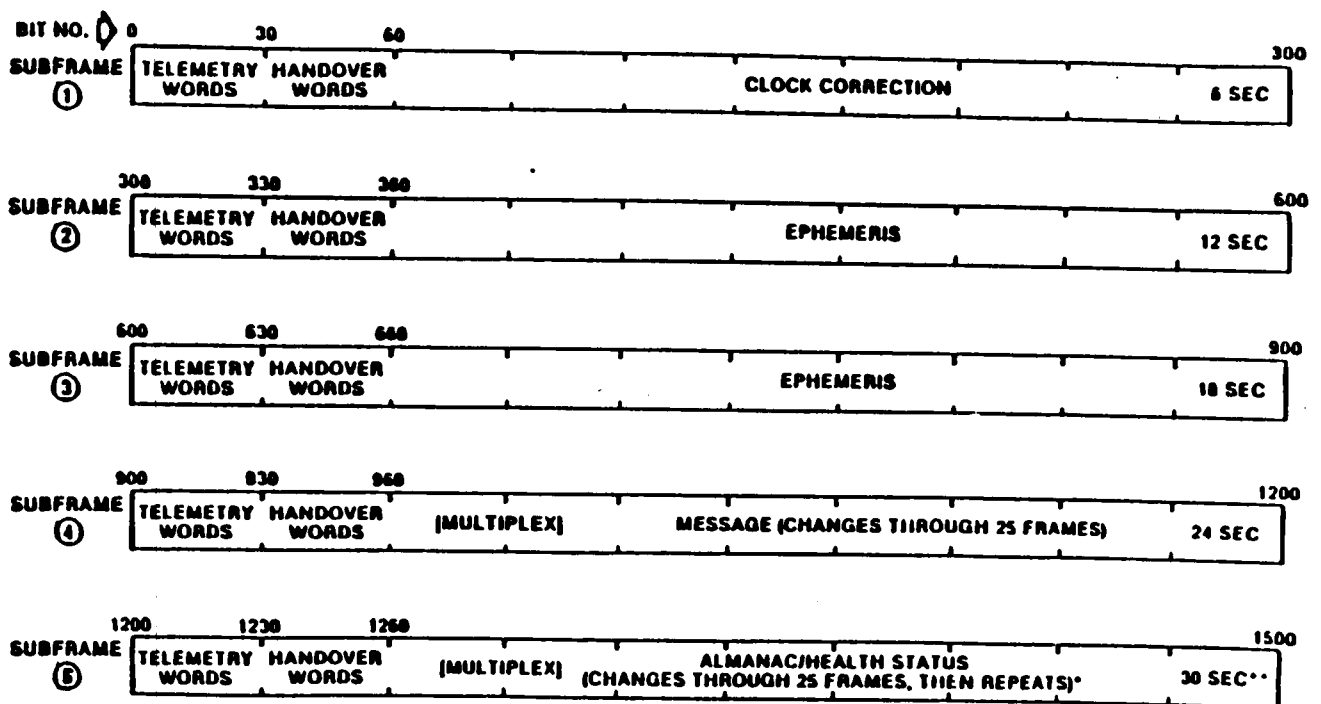


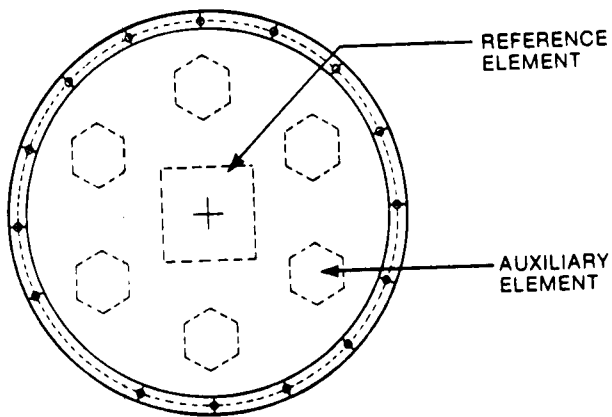
Figure A-13. Terrain Following Route Two

50 Bits Per Second Data Rate

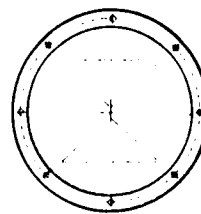


*FORMAT OF FRAME TWENTY-FIVE CHANGES.
 **12.6 MINUTES BEFORE THE ENTIRE MESSAGE REPEATS.

Figure A-14. GPS Sample Data Message Format



Controlled Reception Pattern Antenna (CRPA)

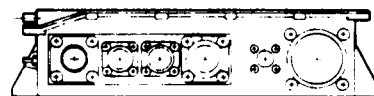


Fixed Reception Pattern Antenna (FRPA)



10-32UNC-2A GROUND
STUD WITH HEX NUT
AND LOCK WASHER

Antenna Electronics



GPS Receiver

63.5 [2.50]
MAX

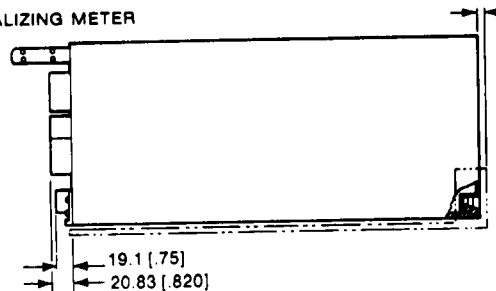
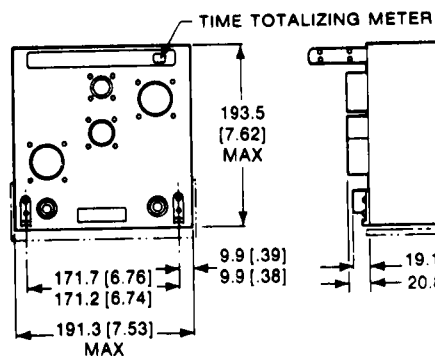
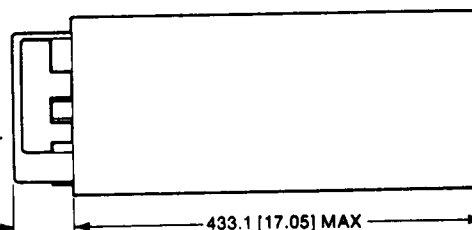


Figure A-15. Collins GPS User Equipment Diagram

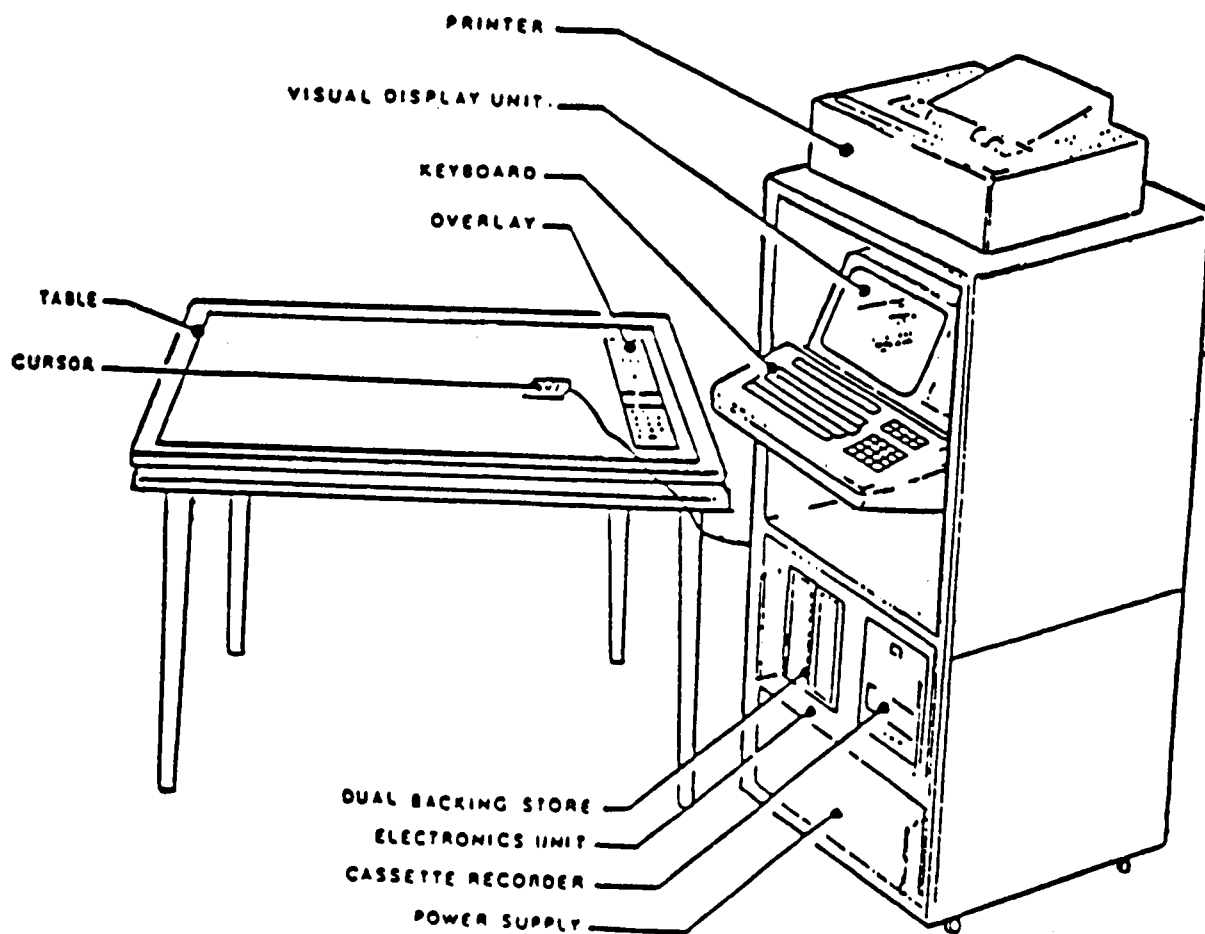


Figure A-16 . Cassette Preparation Ground Station

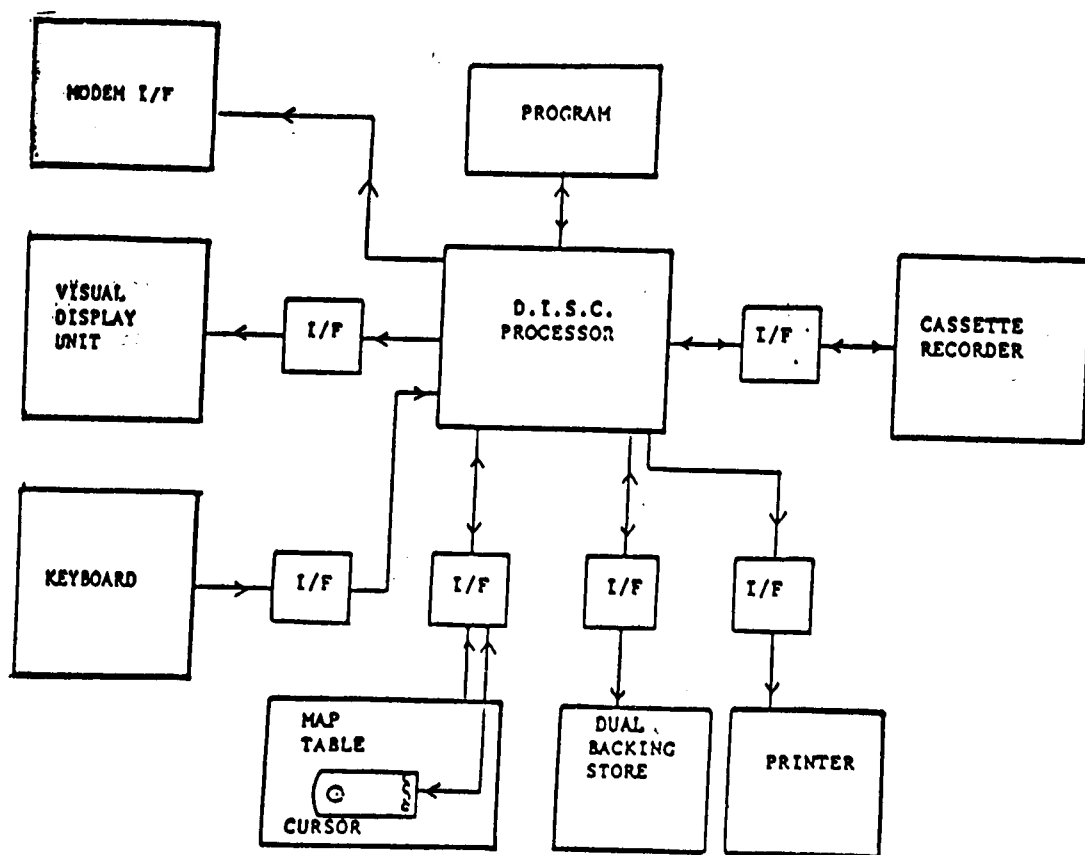


Figure A-17. Proposed Planning System Architecture

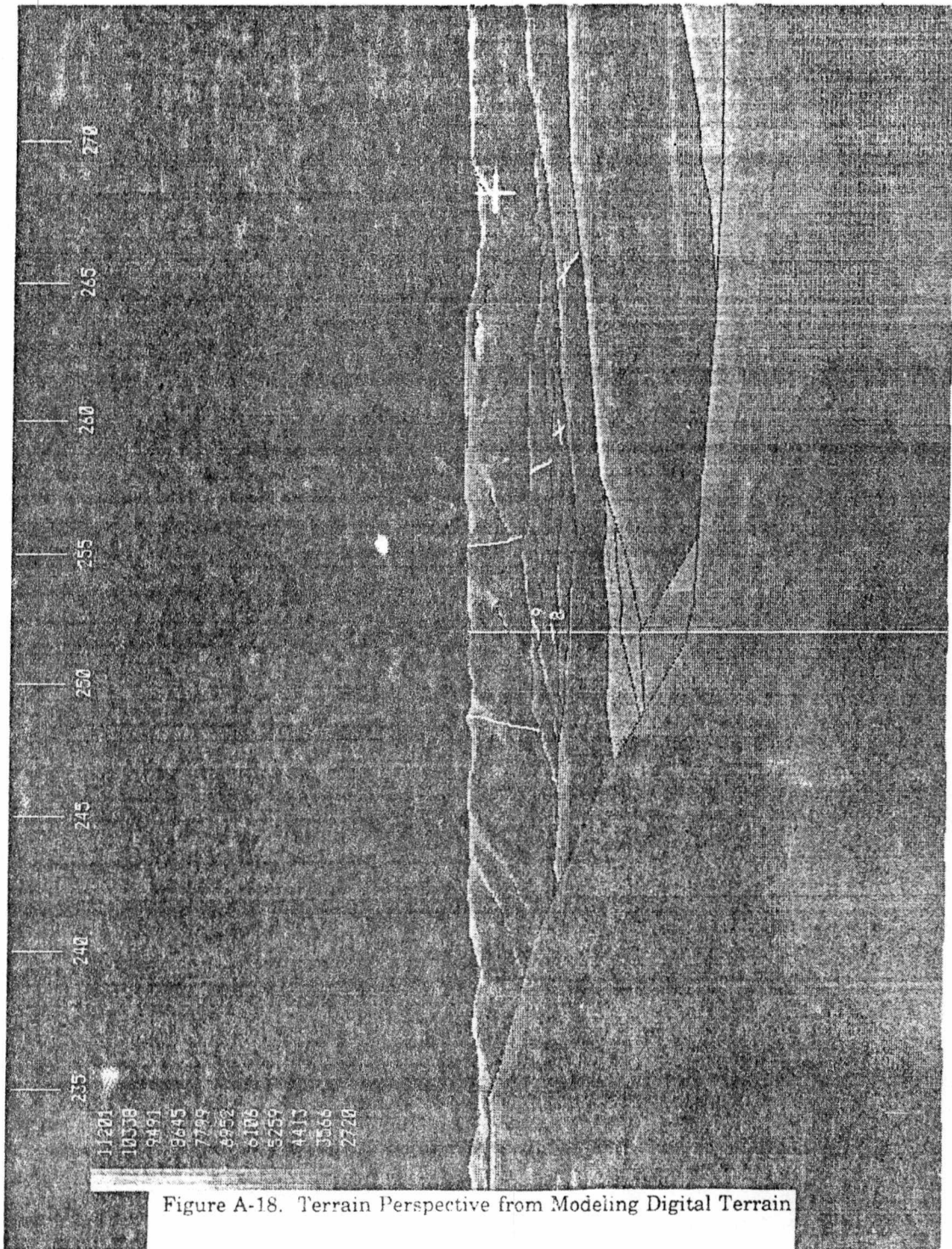


Figure A-18. Terrain Perspective from Modeling Digital Terrain

Table B-1. Tornado Operational Characteristics and Dimensions

PARAMETER	QUANTITY
Length (overall including pitot static boom)	17.23m / 56.52 ft
Wing Span swept full forward	13.91m / 52.59 ft
Wing Span swept full aft	8.56m / 28.10 ft
Height (to top of vertical fin)	5.95m / 19.52 ft
Wheel Base	3.10m / 10.17 ft
Turning Radius	7.08m / 23.25 ft
Empty Weight	13,600 kg / 29,982 lb
Operating Weight (plus full internal fuel)	18,100 kg / 39,903 lb
Operating Weight (plus full internal fuel and 2 external drop tanks)	20,962 kg / 46,212 lb
Maximum Taxi and Takeoff	27,500 kg / 60,627 lb
Maximum Overload Landing	23,500 kg / 50,706 lb
Normal Landing	17,000 kg / 37,478 lb

Table B-2. Main Computer Performance Characteristics

PARAMETER	PERFORMANCE CHARACTERISTIC
MAIN COMPUTER	-----
Data Format	Binary two's complement
Program Level	2
Number of Instructions	55
Control	Microprogram
Internal Oscillator	-----
Clock Frequency	2 MHz
Stability	1×10^{-5} in any 3 hour period
Access	Program Controlled Channel Direct Memory Access (DMA)
Memory	-----
Type	Lithium Ferrite Magnetic Core
Word Length	18 bit
Capacity	32k
Operations	Read/Restore (RR) Clear/Write (CW)
Temperature Range	-55 °C to +85 °C
Electrical Interface	Transistor-Transistor logic compatible, wired outputs

Table B-3. GPS Control Segment Locations and Functions

LOCATION	FUNCTION
Colorado Springs	Control and Monitor
Hawai	Monitor
Diego Garcia	Monitor
Kwajalene	Monitor
Vandenburg AFB	Monitor and Backup Control

Table B-4. GPS User Equipment Specifications

SYSTEM PERFORMANCE (typical)⁽¹⁾

Receiver antijam ⁽²⁾: 47 dB J/S (54 dB J/S with INS aiding).

CRPA antijam enhancement: Additional 40 dB J/S for CW jammer, 35 dB J/S for 20 MHz noise jammer.

Reaction time (elapsed time from power on to first accurate solution output): 4.5 minutes.

Time-to-first-fix (elapsed time from completed initialization to first accurate solution output): 1.5 minutes.

Solution update rate: 1 Hz (can be propagated up to 20 Hz).

Host vehicle dynamics capable of being tracked:		Accuracies:	
Velocity	1200 m/s	Position	10 m
Acceleration	118 m/s/s	Velocity	0.1 m/s
Jerk	180 m/s/s/s	Time	50 ns
Yaw	±1 rad/s, ±3 rad/s/s		
Pitch	±1 rad/s, ±6 rad/s/s		
Roll	±5.5 rad/s, ±17.5 rad/s/s		

SPECIFICATIONS (typical)

PHYSICAL	CRPA	FRPA	ANTENNA ELECTRONICS	GPS RECEIVER	CDU	DATA LOADER
Weight	2.0 kg (4.5 pounds)	0.45 kg (1 pound)	3.6 kg (8 pounds)	13.5 kg (30 pounds)	3.6 kg (8 pounds)	0.45 kg (1 pound)
Cooling	N/A	N/A	Convection/ Conduction	Convection	Convection	Convection
Environment	MIL-E-5400 Class 3	MIL-E-5400 Class 3	MIL-E-5400 Class 2	MIL-E-5400 Class 2	MIL-E-5400 Class 1	MIL-E-5400 Class 2
Power	N/A	N/A	18 watts	98 watts	30 watts	2.9 watts

Input power: 115 V ac/400 Hz single-phase.

Interfaces ⁽³⁾: MIL-STD-1553 A/B compatible (Fire Control Computer, Inertial Navigation Unit, Central Air Data Computer, Fire Control/Navigation Panel)

Number of receiver channels: 5

(1) Unaided system performance unless otherwise stated.

(2) Referenced to nominal signal power of -163 dBw.

(3) USAF F-16A application. Other mix of digital and analog interfaces can be provided.

```

PROGRAM TERRAIN

CHARACTER j
INTEGER*4 i
INTEGER bubble_array(500),bubble_point,clobber_array(500)
1 ,clobber_point,i,j,rl,run_no,k,ride,kvel,acagl(500)
2 ,clobber,bubble_miss,agl,vel,data_points
REAL gpsalt,minalt,terra(500,3),erralt,gpserr,pob,poc
1 ,init_range,range,eterra(500,3),actual(500)
2 ,runin(500),rrl,hore
data_points = 0
j = CHAR(09)
run_no = 1
pob = 0.0
poc = 0.0

C      Open the DMA data file( Level 1 ). The altitude data
C      read by this program is expressed in feet MSL.
OPEN (UNIT=12 , STATUS='old' , FILE='a4.a4' , ERR=9999)
OPEN (UNIT=13 , STATUS='old' , FILE='x4.x4' , ERR=9999)
OPEN (UNIT=14 , STATUS='old' , FILE='b4.b4' , ERR=9999)

C      Read the range between each data point for this Lat and Lon.
READ (13,10,ERR=9999)init_range
range = init_range

C      Begin loop to read DMA data into the array,
C      and determine the range between each data point.
1      data_points = data_points + 1
      READ (12,11,END=9998,ERR=9999)terra(data_points,1)
      READ (13,11,END=9998,ERR=9999)terra(data_points,2)
      READ (14,11,END=9998,ERR=9999)terra(data_points,3)
      runin(data_points) = range
      range = init_range + range
      go to 1
9998  data_points = data_points - 1
      CLOSE(unit=12 , status='keep')
      CLOSE(unit=13 , status='keep')
      CLOSE(unit=14 , status='keep')

C      Open the input file.
OPEN (UNIT=15 , STATUS='old' , FILE='short_run.dat' , ERR=9999)

C      Open the output file to record statistical information for a series
C      or runs.
OPEN (UNIT=17 , STATUS='new' , FILE='dummy.dat' , ERR=9999)
WRITE(17,8)

C      Allow the user to initialize his desired altitude.
2      CALL AGL_SELECT(agl,*77)

C      Allow the user to select the desired ride setting for this run.
      CALL G_SELECT(ride,*77)

C      Allow the user to select a velocity for this particular run.

```

FORTRAN Simulation Program


```

      CALL VELOCITY_SELECT(vel,kvel,*77)

C      Allow the user to select any GPS degradation.
      CALL GPS_DEGRADE(rl,*77)

C      Open the plot file to record plot data for one run.
      OPEN (UNIT=11 , STATUS='new' , FILE='plot.dat' , ERR=9999)

C      Begin loop to estimate the error associated with the DMA data.
      DO ij = 1,data_points,1
      CALL TERRAIN_ERROR(terra(ij,1),terra(ij,2),terra(ij,3),
1 eterra(ij,1),eterra(ij,2),eterra(ij,3))
      END DO

C      Begin loop to determine the errors induced by GPS FOM by first
C      selecting a lefthand or righthand path.
      k = 1
      if(RAN(1) .GT. 0.5) k = 3
      DO ij = 1,data_points,1
      CALL GPS_ERROR(eterra(ij,1),eterra(ij,2),
1 eterra(ij,3),rl,actual(ij),k,rrl,hore)
      END DO
      bubble_point = 0
      clobber_point = 0
      do ij = 1,data_points,1

C      Call subroutine to compute aircraft elevation based on G selection.
      CALL G_COMPUTE(agl,acagl(ij),ride)

C      Call subroutine to record clobbers and near misses.
      CALL CLOSE_CALL(ij,bubble_array,bubble_point
1 ,clobber_array,clobber_point,eterra(ij,2),actual(ij)
2 ,acagl(ij))
      END DO

C      Write out the following information to the plot file.
C      runin distance
C      DMA elevation data with error adjustment
C      Actual elevation flight path data
      DO ij = 1,data_points,1
      WRITE (11,12)j,runin(ij),j,eterra(ij,2),
1 j,actual(ij),j,runin(bubble_array(ij)),
2 j,runin(clobber_array(ij)),j,acagl(ij)
      END DO

C      Write out information for this run only.
      write(17,9)run_no,ride,agl,kvel,rrl,rl
1 ,bubble_point,clobber_point,hore
      run_no = run_no + 1
      CLOSE(unit=11 , status = 'keep')
      go to 2
77 CONTINUE

C      Call subroutine to output stastical information
      CALL STATS(bubble_point,

```

FORTRAN Simulation Program

```

1          clobber_point,data_points,pob,poc)

      CLOSE(UNIT=3 , STATUS='keep')
      CLOSE(UNIT=15 , STATUS='keep')
      CLOSE(UNIT=11 , STATUS='keep')
      CLOSE(UNIT=17 , STATUS='keep')
9999      STOP
8          format(T2,'RUN',T8,'RIDE',T17,'ALTITUDE',T30,'A/C VEL',
1          T45,'GPS',T57,'GPS',T64,'BUBBLE',T74,'AIRCRAFT',
2          T87,'HORIZ',/,
3          T2,'NO.',T7,'SETTING',T17,'CLEARANCE',T29,'(knots)',
4          T41,'DEGRADIATION',T57,'FOM',T64,'IMPACTS',T75,'IMPACTS',
5          T87,'ERROR',/)
9          format(t2,i3,t9,i2,t18,i5,t31,i3,
1         t44,f6.2,t58,i1,t65,i3,t76,i3,t87,f4.0,'%')
10         format(f5.2)
11         format(f7.0)
12         format(a,f8.0,a,f8.0,a,f8.0,a,f8.0,a,f8.0,a,i8)
13         format(a,i19,a,f19.0,i25)
14         format(23X,'CLOBBER AT',/,15X,'RANGE',17X,'ALTITUDE',
1         17X,'VELOCITY',/)
15         format(23X,'BUBBLE HIT',/,15X,'RANGE',17X,'ALTITUDE',
1         17X,'VELOCITY',/)
16         format(/,5X,'The probability of a bubble contact is',f4.0,'%')
17         format(/,5X,'The probability of a clobber is',f4.0,'%')
      END

```

FORTRAN Simulation Program

```

SUBROUTINE TERRAIN_ERROR(l,c,r,t1,t2,t3)
C   This routine adds vertical errors associated with DTED Level 1
C   data. The DTED data is expressed as a linear error at the 90%
C   confidence level with an absolute accuracy requirement of + or -
C   30 meters.
INTEGER*4 i
REAL absacc,c,l,r,t1,t2,t3,t(3)

absacc = 30.0

DO ij = 1,3,1
C   Force 90% of the DMA data points to have less than a 10 meter error.
  if(RAN(i) .LE. 0.90) absacc = 10.0

C   Convert the absolute accuracy requirement from meters to feet.
  t(ij) = absacc * 39.0 / 12.0

C   Generate a random error based on the previous absolute accuracy.
  t(ij) = RAN(i) * t(ij)

C   Generate another random number to seed a positive or negative
C   altitude change.
  if (RAN(i) .gt. .5) t(ij) = -t(ij)
END DO

C   Add this terrain error to the actual terrain elevation.
  t1 = l + t(1)
  t2 = c + t(2)
  t3 = r + t(3)
  return
END

```

FORTRAN Simulation Program

```

      SUBROUTINE GPS_DEGRADE(r1,*)
C      Allow the user to input the degree of GPS degradation associated with
C      the GPS system.
      INTEGER r1
11     WRITE(6,13)
      READ (15,14,END = 77)r1
C      if(r1.lt.0.or.r1.gt.9)go to 11
13     FORMAT(/,10x,'GPS FIGURE OF MERIT VALUES',/,
1       9X,'FOM',T20,'ESTIMATED POSITION ERROR',/,
1       10X,'0',T20,'No position error',/,
1       10X,'1',T20,'Less than 25 meters spherical error',/,
2       10X,'2',T20,'Less than 50 meters spherical error',/,
3       10X,'3',T20,'Less than 75 meters spherical error',/,
4       10X,'4',T20,'Less than 100 meters spherical error',/,
6       5X,'ENTER THE ESTIMATED FOM :',%)
      if(r1 .GT. 4) r1 = 4
14     FORMAT(I1)
      return
77     RETURN 1
      end

```

FORTRAN Simulation Program

```

SUBROUTINE GPS_ERROR(t1,t2,t3,r1,act,k,r1,hore)
REAL act,dif,r1,ran_elev,herr,hore,t1,t2,t3,t(3)
INTEGER*4 i
INTEGER r1,k
C      This subroutine uses the FOM entered by the user to calculaate
C      the drift of the aircraft due to GPS errors. The aircraft drift
C      will determine the actual elevation of the terrain over which the
C      aircraft flies.

C      If no error then return.
      if(r1 .EQ. 0) act = t2
      if(r1 .EQ. 0) hore = 0.0
      if(r1 .EQ. 0) return
      r1 = r1
      t(1) = t1
      t(2) = t2
      t(3) = t3

C      Find difference in two elevations.
      dif = t(2) - t(k)

C      Find the maximun horiz. error in feet.
      hore = r1 * 0.25

C      Take a random elevation for the drift.
      ran_elev = hore * ran(i) * dif

C      Create the actual terrain elevation.
      act = t(2) + ran_elev

C      Find the difference in meters.
      difm = dif * 12.0 / 39.0

C      Adjust for percentage.
      hore = hore * 100.0
      return
END

```

FORTRAN Simulation Program

```

SUBROUTINE G_SELECT(ride,*)
  INTEGER ride
C   This routine will allow the user to dial in the maximum
C   number of G's for this run in.
  WRITE(6,21)
  WRITE(6,22)
11  WRITE(6,23)
  READ(15,24,END = 77)ride
C   if(ride.LT.1.OR.ride.GT.3)go to 11
21  FORMAT(/,T10,'RIDE',T25,'DESIRED MAXIMUM',T46,
1    'DESIRED MAXIMUM',/,T9,'SETTING',T24,
2    'PUSH OVER COMMAND',T46,'PULL UP COMMAND')
22  FORMAT(/,' 1',T10,'HARD',T29,'+0.05g',T50,'+3g',/,
1      ' 2',T10,'MED' ,T29,'+0.25g',T50,'+2g',/,
2      ' 3',T10,'SOFT',T29,'+0.50g',T50,'+1.5g')
23  FORMAT(//,' SELECT THE NUMBER ASSOCIATED WITH THE DESIRED R
1IDE SETTING:',$)
24  FORMAT(I1)
  return
77  RETURN 1
  END

```

FORTRAN Simulation Program

```

SUBROUTINE AGL_SELECT(agl,*)
INTEGER agl
WRITE(6,11)
READ(15,12,END = 77) agl
11  format(' ENTER THE STARTING ALTITUDE(ft) FOR THIS SCENARIO:',S)
12  format(i5)
    return
77  return 1
    END

```

FORTRAN Simulation Program

```

SUBROUTINE VELOCITY_SELECT(vcl,kvel,*)
  INTEGER kvel,vcl
  REAL vvcl
  WRITE(6,11)
  READ(15,12,END = 77)vcl
11  format(/,' ENTER THE STARTING VELOCITY(knots) FOR THIS SCENARIO:'
1    ,5)
  kvel = vcl

C    Convert knots to feet per sec.
  vvcl = vcl
  vvcl = vvcl / 360 * (1.1508 * 5280)
  vcl = vvcl
12  format(15)
  return
77  RETURN 1
END

```

FORTRAN Simulation Program


```
SUBROUTINE G_COMPUTE(agl,fagl,ride)
  INTEGER agl,fagl,ride
  REAL fride
  INTEGER*4 i
  fride = ride
  fride = ((fride / 3.0) * 10.0) * RAN(1)
  fagl = fride
  fagl = agl - fagl

  return
END
```

FORTTRAN Simulation Program

```

      SUBROUTINE CLOSE_CALL(dp,bubble_array,bubble_point,
1  clobber_array,clobber_point,g1,gpsalt,agl)

      INTEGER bubble_array(500),bubble_point,agl,
1  clobber_array(500),clobber_point,dp

      REAL gpsalt,g1,ac_alt,clobber,bubble_miss

      ac_alt = g1 + agl
      clobber = ac_alt - (gpsalt + 15.0)

      IF (clobber.LE.0.0) THEN
         clobber_point = clobber_point + 1
         clobber_array(clobber_point) = dp
      END IF

      bubble_miss = ac_alt - (gpsalt + 50.0)
      IF (bubble_miss.LE.0.0) THEN
         bubble_point = bubble_point + 1
         bubble_array(bubble_point) = dp
      END IF

      return
      END

```

FORTRAN Simulation Program

```

SUBROUTINE STATS(bubble_point,
1 clobber_point,data_points,pob,poc)
  INTEGER bubble_point,clobber_point,data_points
  REAL rbp,rcp,rdp,pob,poc

C   Convert to reals for necessary calculations.
  rbp = bubble_point
  rcp = clobber_point
  rdp = data_points

  if(data_points.LE.0)return

C   Compute the probability of a clobber.
  IF(clobber_point.GT.0) THEN

      poc = rcp / rdp * 100
  END IF

C   Compute the probability of a bubble hit.
  IF(bubble_point.GT.0) THEN

      pob = rbp / rdp * 100
  END IF
  return
END

```

FORTRAN Simulation Program

```
Path A information
Start Latitude 36.123
Start Longitude: 117.119
End Latitude:    36.213
End Longitude:   117.041
5997
5997
6056
6056
6004
6099
6099
6099
6168
6280
6280
6280
6345
6411
6411
6411
6411
```

FORTRAN Simulation Program

Trajectory information
Distance per point: 99.66 feet.
Start Latitude: 36.122
Start Longitude: 117.118
End Latitude: 36.212
End Longitude: 117.041
5869
5869
5869
5869
5974
5981
5981
5981
6007
6145
6145
6145
6286
6391
6391
6398

FORTRAN Simulation Program

Path B information
Start Latitude 36.122
Start Longitude: 117.118
End Latitude: 36.212
End Longitude: 117.040

5869
5869
5873
5981
5981
5981
6102
6145
6145
6145
6391
6391
6391
6391
6522
6522
6522

FORTRAN Simulation Program

RUN NO.	RIDE SETTING	ALTITUDE CLEARANCE	A/C VEL (knots)	GPS DEGRADATION	GPS FOM	BUBBLE IMPACTS	AIRCRAFT IMPACTS	HORIZ ERROR
1	1	200	420	0.00	0	0	0	0.%
2	1	200	420	1.00	1	0	0	25.%
3	1	200	420	2.00	2	0	0	50.%
4	1	200	480	3.00	3	1	0	75.%
5	1	200	480	4.00	4	28	12	100.%
6	1	200	480	4.00	4	13	7	100.%
7	1	200	480	4.00	0	0	0	0.%
8	1	200	540	1.00	1	0	0	25.%
9	1	200	540	2.00	2	0	0	50.%
10	1	200	540	3.00	3	1	1	75.%
11	1	200	540	4.00	4	36	16	100.%
12	1	200	600	4.00	4	9	7	100.%
13	1	200	600	1.00	1	0	0	25.%
14	1	200	600	3.00	3	11	5	75.%
15	1	200	650	4.00	4	25	14	100.%
16	2	200	420	4.00	0	0	0	0.%
17	2	200	420	1.00	1	0	0	25.%
18	2	200	420	2.00	2	0	0	50.%
19	2	200	480	3.00	3	10	3	75.%
20	2	200	480	4.00	4	10	5	100.%
21	2	200	480	4.00	4	25	12	100.%
22	2	200	480	1.00	1	0	0	25.%
23	2	200	540	2.00	2	2	0	50.%
24	2	200	540	4.00	4	28	11	100.%
25	2	200	540	4.00	0	0	0	0.%
26	2	200	540	3.00	3	7	4	75.%
27	2	200	600	1.00	1	0	0	25.%
28	2	200	600	3.00	3	0	0	75.%
29	2	200	600	2.00	2	0	0	50.%
30	2	200	650	1.00	1	0	0	25.%
31	2	200	650	2.00	2	0	0	50.%
32	3	200	420	2.00	0	0	0	0.%
33	3	200	420	1.00	1	0	0	25.%
34	3	200	420	2.00	2	0	0	50.%
35	3	200	480	3.00	3	11	2	75.%
36	3	200	480	4.00	4	9	5	100.%
37	3	200	480	1.00	1	0	0	25.%
38	3	200	540	1.00	0	0	0	0.%
39	3	200	540	2.00	2	0	0	50.%
40	3	200	540	3.00	3	2	1	75.%

FORTRAN Simulation Program

VITA

John William Scanlan II was born in Clifton Forge, VA on March 28, 1954. He was raised and attended elementary schools in Lawrence, KS, and in 1972 graduated from Lawrence High School. He attended the University of Kansas on a full athletic scholarship and in the spring of 1976 received a Bachelor of General Studies degree in Aquatic Biology. Mr. Scanlan, his wife Amy, and daughter Shannon moved to Kansas City where he worked for six years as a marketing representative for a printing firm and a Health Maintenance Organization.

In the fall of 1981, he completed Naval Aviation Officer Candidate School and received a commission as an Ensign. The following fall he was designated a Naval Flight Officer and moved from Pensacola, FL to Whidbey Island, WA for advanced flight training. LT Scanlan was transferred to Attack Squadron Fifty-Five where he served four years until his selection to the United States Navy Test Pilot School (USNTPS). Since graduation from USNTPS in December 1987, he has served in Air Test and Evaluation Squadron Five as the Operational Test Director for Chief of Naval Operations Projects including the Navy's advanced tactical bomber (A-12) and other classified programs.

LT Scanlan was awarded a Navy Achievement Medal in 1989 for his work on the A-12 aircraft. He has received orders to serve in Attack Squadron One Sixty Five and will transfer to Whidbey Island in August of 1990.