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Coordinated Parallel Runway Approaches

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Abstract

The current air traffic environment in airport terminal areas experiences substantial delays when weather conditions deteriorate to Instrument Meteorological Conditions (IMC). Expected future increases in air traffic will put additional pressures on the National Airspace System (NAS) and will further compound the high costs associated with airport delays. To address this problem, NASA has embarked on a program to address Terminal Area Productivity (TAP). The goals of the TAP program are to provide increased efficiencies in air traffic during the approach, landing, and surface operations in low-visibility conditions. The ultimate goal is to achieve efficiencies of terminal area flight operations commensurate with Visual Meteorological Conditions (VMC) at current or improved levels of safety.

This report documents the results of a study, which addresses the problem of achieving independent parallel runway approaches to closely-spaced runways in IMC weather. More specifically, a flight-deck centered system approach is considered that monitors progress of aircraft performing simultaneous, independent parallel approaches (in IMC), provides timely and reliable cautions and alerts in the event of aircraft deviations from their intended flight paths, and provides guidance for appropriate evasive actions to be taken by the flight crew to avoid an incident.

This study was conducted under the NASA TAP program and documents the top-level system concept. This initial study focused primarily on the alerting portion of the system and provides an indication to the ultimate limits of reduction in runway spacings that may be accommodated. A number of important issues require further investigation before this concept can gain acceptance in the operational environment.

Table of Contents

Table of Contents

List of Figures

List of Figures

List of Tables

Acknowledgments

The author would like to thank Scott Chamberlain, Jim Klein, Joel Wichgers, Ross Beins, Stan Zimmerman, Jeff Spicer, Pat Bulten, Jim Doty, and Tom Sharpe for their contributions to this study.

Scott Chamberlain's contributions in developing the AILS simulation program and AILS alerting algorithms were invaluable to our effort. Jim Klein provided the assessment and cost comparison of existing and evolving runway monitoring systems other than AILS and consulted throughout the project. Joel Wichgers' analysis of lateral error budgets associated with various types of runway approaches (manual/autoland, ILS/GPS/augmented GPS) provided an important input to the study. Ross Beins and Stan Zimmerman ably piloted numerous runway approaches (both normal approaches and scripted blunder approaches) in our Fokker 70 part-task simulator, providing real-world aircraft state data that served as flight track templates for evaluating the AILS alerting algorithms. Jeff Spicer provided all the data collection support for gathering the flight track template data files. Pat Bulten supported the analysis of aircraft data and communication requirements and Jim Doty demonstrated surveillance accuracy that can be achieved by a precision runway monitor based on multilateration surveillance of aircraft transponder replies. Tom Sharpe served as both program manager and technical consultant throughout the study.

Special thanks also to Jim Kuchar and Brenda Carpenter from MIT for our close working relationship and information exchanges during the development of AILS alerting algorithms.

1.0 Introduction

With the advent of global, satellite-based navigation and data link communications technology, the aviation industry is now able to address air space solutions that provide for more efficient travel while maintaining safety. Two such areas are the Future Air Navigation System / Air Traffic Management (FANS/ATM) system and airport terminal area capacity improvement initiatives. Much focus is currently being given toward the development of FANS/ATM since immediate cost benefits are expected. To a somewhat lesser extent, programs and flight tests directed toward improving the efficiency of airport terminal area operations are also being addressed by the aviation community.

FANS/ATM

FANS/ATM is moving toward the concept of free flight, where aircraft can choose and negotiate preferred flight paths under the watchful eye of the ATM ground system. This compares to today's system where aircraft are assigned to relatively rigid flight paths and air corridors under direct control by the air traffic control system. Free flight allows selection of routes that take advantage of wind patterns, and allows aircraft to operate at preferred performance levels. In FANS/ATM, the role of air traffic control (ATC) is to manage the air traffic environment by monitoring the flight progress and future flight path intent of aircraft in free flight. Only in the event of potential conflicts between flight paths will ATC intervene, providing the necessary coordination of air routes between aircraft. Free flight is expected to result in significant cost savings to the air travel industry, and will accommodate expected increases in air traffic.

Airport Terminal Area Capacity Improvement Programs

With the expected benefits of free flight and the expected increases in air traffic, it becomes paramount for the aviation industry to address the congestion problems at major airport terminals. Substantial airport delays are already occurring at the nations largest airports and are expected to increase as traffic loads increase. While construction of new airports or expansion of existing airports will provide additional capacity, this carries a substantial price tag. The Federal Aviation Administration (FAA) is actively pursuing initiatives to increase the capacity of airport terminal areas.

Improved ATC procedures, terminal automation support to controllers, additional Instrument Landing Systems, improved controller display aids, improved utilization of multiple runways, etc., are all expected to increase airport capacity. The FAA Airport Surface Traffic Automation (ASTA) program is also addressing the problem of surface operations during low-visibility conditions. Under the Terminal Air Traffic Control Automation (TATCA) program, the FAA is developing software automation tools that assist the controllers and thus allow increases in airport capacity. Some of the automation tools are Converging Runway Display Aid (CRDA) and Controller Automated Spacing Aid (CASA). The Center-TRACON Automation System (CTAS) jointly being developed by FAA and NASA Ames Research Center provides an additional set of integrated tools that support the approach and departure of aircraft. The Traffic Management Advisor (TMA), Descent Advisor (DA), Final Approach

Spacing Tool (FAST), and the Expedite Departure Path (EDP) tools all assist the controller by computing an optimum traffic plan and advising the controller in scheduling arrivals and departures.

In addition to FAA efforts, NASA Langley and NASA Ames Research Centers are also working to improve airport capacities. NASA's Terminal Area Productivity (TAP) program is intended to support the industry with the development of appropriate technologies, system solutions, and also to involve industry in achieving improved efficiency and safety of terminal area operations, particularly during low-visibility weather conditions.

The major components of TAP are 1) to increase the number of approaches/landings per runway by reducing in-trail and lateral separations between aircraft, 2) ATC automation providing optimized sequencing, scheduling and control of aircraft, and allowing rapid runway and airspace reconfiguration, 3) provide low-visibility landing and surface operations via integrated cockpit aids; navigation, guidance and controls; and imaging sensors where possible, and 4) integration of aircraft-ATC automation functions.

Scope of Report

The scope of this study and associated report is in support of NASA's TAP program that addresses reduced lateral separation between aircraft, i.e., to determine recommendations for the minimum allowable spacing of parallel runways that can support independent parallel runway approaches during Instrument Meteorological Conditions (IMC). The NASA group addressing this problem is the Airborne Information for Lateral Spacing (AILS) team. The program is conducted by NASA Langley and NASA Ames Research Centers. Other team members are Lockheed Engineering Services, MIT and Rockwell Collins Avionics.

While the overall AILS system concept, objectives and goals are presented in section 1.3, the primary focus of this report is to document Collins' contribution to the AILS study and system concept development. Where appropriate, this report also references activities of other team members in support of AILS.

The emphasis of Collins' AILS study has been on the development and evaluation of prototype AILS alerting algorithms that provide reliable and timely warning against inadvertent aircraft deviations or blunders by one aircraft into the flight path of the other aircraft during independent parallel runway approaches. The study also addresses avionics sensor and data communications requirements necessary to enable the AILS alerting concept, defines airspace infrastructure requirements, and provides an assessment of NASA's Boeing 757 Transport Systems Research Vehicle (TSRV) avionics system to support flight tests of AILS. The study concludes with a cost comparison of the flight-deck centered AILS alerting system to other existing and evolving parallel runway monitoring systems.

1.1 Background

The number of flight delays experienced each year continues to increase as air traffic demand is placing a greater strain on the available capacity of the National Airspace System (NAS). In 1989 alone about 1,600,000 hours of delay time occurred, representing about 12 percent of US carrier fleet capacity [1]. According to a Boeing Market Outlook, domestic air carrier flights are expected to increase 50% from 1989 to 2010. Without substantial NAS capacity improvements, flight delays will continue to increase.

A major contributor to flight delays is the capacity of airports. As indicated, a number of airport terminal area capacity improvement initiatives are currently being pursued by FAA, NASA (TAP program), and others. An important bottleneck in traffic throughput at airports is the number of approach operations per runway. Greatest throughput can be achieved for independent parallel runway approaches to multiple runways. For closely-spaced runways, it may become necessary to stagger aircraft on alternate runways during approach to assure sufficient lateral spacing, i.e., parallel runway approaches are dependent.

Maximum approach throughput rates are achieved for independent parallel runway approaches in Visual Meteorological Conditions (VMC). According to Boeing simulation results, independent approach throughput rates in IMC are reduced by 16% versus VMC, and dependent parallel approach throughput is reduced up to 48% during Instrument Flight Rule (IFR) conditions [1]. Thus significant delays can be avoided during IMC and IFR conditions if independent parallel approach operations can be sustained.

1.2 Current Runway Spacings for Independent Parallel Approaches

A history of simultaneous parallel approaches [1] indicates how allowable runway spacings have been reduced over time, from 6,200 ft spacings at J.F. Kennedy and Washington-Dulles airports (early 1960's) to current allowable spacings. In VMC, runway spacings for independent approaches can be as low as 700 ft. In IMC (runway visual range at or below 3 miles or ceiling at or below 1,000 ft), independent parallel approaches are allowed to runway spacings down to 4,300 ft. The primary factors that limit runway spacing to 4,300 ft in IMC are the surveillance update rate and accuracy of the secondary surveillance radar (SSR). Conventional SSR's provide updates at 4.8 seconds intervals (antenna rotation period) and main beam accuracy of 5 milliradians in azimuth.

MITRE Corporation performed a study in 1981 that examined the relationship of surveillance update rate and accuracy to allowable runway spacing and concluded that for 1 milliradian accuracies and 1 sec surveillance update rates the minimum achievable runway spacing for independent parallel approach is 3,000 ft [2].

Based on MITRE's findings, the FAA has developed a Precision Runway Monitor (PRM) system that utilizes an improved SSR [3] that allows a reduction in runway spacing from 4,300 ft to 3,400 ft for independent parallel approaches in IMC. Two types of systems were developed; one using a 2.4 second update rate, using back-to-back antenna beams on a conventional SSR with improved azimuthal accuracy of 1 milliradian, and an electronically-scanned (E-scan) directional antenna with 1 milliradian accuracy. Update rate on E-scan surveillance interrogations were set at 0.5 sec.

The PRM system provides surveillance replies to a controller display that depicts both approach paths, a Non-Transgression Zone (NTZ) between runways, and displays current aircraft location along with a 10 second trend vector of predicted aircraft heading. Aircraft tracks are maintained based on surveillance replies and an alpha-beta tracking filter that uses range and range-rate to update position reports. The controller monitors the conformance of each aircraft to its respective approach path and issues a breakout warning to the threatened aircraft in the event of an aircraft transgression into the NTZ. The warning is issued via the ATC VHF voice radio.

While prototype PRM systems have been demonstrated, there are only a limited number of PRM systems that are in the commissioning stage. A concern has been raised about the possibility of a temporary blockage of the communications channel in the event the controller needs to issue a breakout warning. The FAA is continuing to explore PRM alternatives based on surveillance concepts using Automatic Dependent Surveillance (ADS-B) position squitters by aircraft, and multilateration, i.e., triangulation, of aircraft replies by multiple ground sensors.

1.3 AILS System Concept

As indicated, this study supports NASA's Airborne Information for Lateral Spacing (AILS) project that falls under the umbrella of TAP. The primary objective and goal of this project is to develop a flight deck based system to monitor independent parallel runway approaches in IMC to achieve further reductions in runway spacings beyond the 3,400 ft limit provided by the PRM.

As illustrated in Figure 1-1, the AILS system, supporting coordinated parallel runway approaches, consists of two main components; 1) a parallel approach Required Navigation Performance (RNP) conformance monitoring sub-system of own aircraft's (i.e., also termed evader aircraft) adherence to its approach path or tunnel, and 2) a surveillance and alerting sub-system that tracks the aircraft state of the other aircraft (i.e., also termed intruder aircraft) in the event of a deviation or blunder by the intruder into own aircraft's flight path. An AILS avionics system thus consists of an AILS Parallel Runway RNP sub-system and an AILS Alerting sub-system to serve as a back-up system in the event of a failure by the intruder's AILS RNP avionics.

Also depicted in Figure 1-1 for the purpose of baseline comparison is the PRM system discussed earlier. The AILS system seeks to improve upon the PRM's 3,400 ft parallel runway spacing limit by utilizing improved aircraft state surveillance and by eliminating the need for uplink of blunder warnings from ATC.

The AILS system provides the flight crew with situational awareness during parallel approaches in IMC via display information on the Navigation Display (ND) and Primary Flight Display (PFD). It also provides on-board caution and warning alerts of parallel approach RNP violations by own aircraft and blunder alerts due to flight path deviations by the intruder aircraft.

The reference to the TSRV simulator in Figure 1-1 is included to note planned flight simulator experiments that will evaluate the performance of AILS system concepts by monitoring a number of dependent variables (closest encounter, pilot response time, and subjective comments on the performance of the system) as runway spacing is varied.

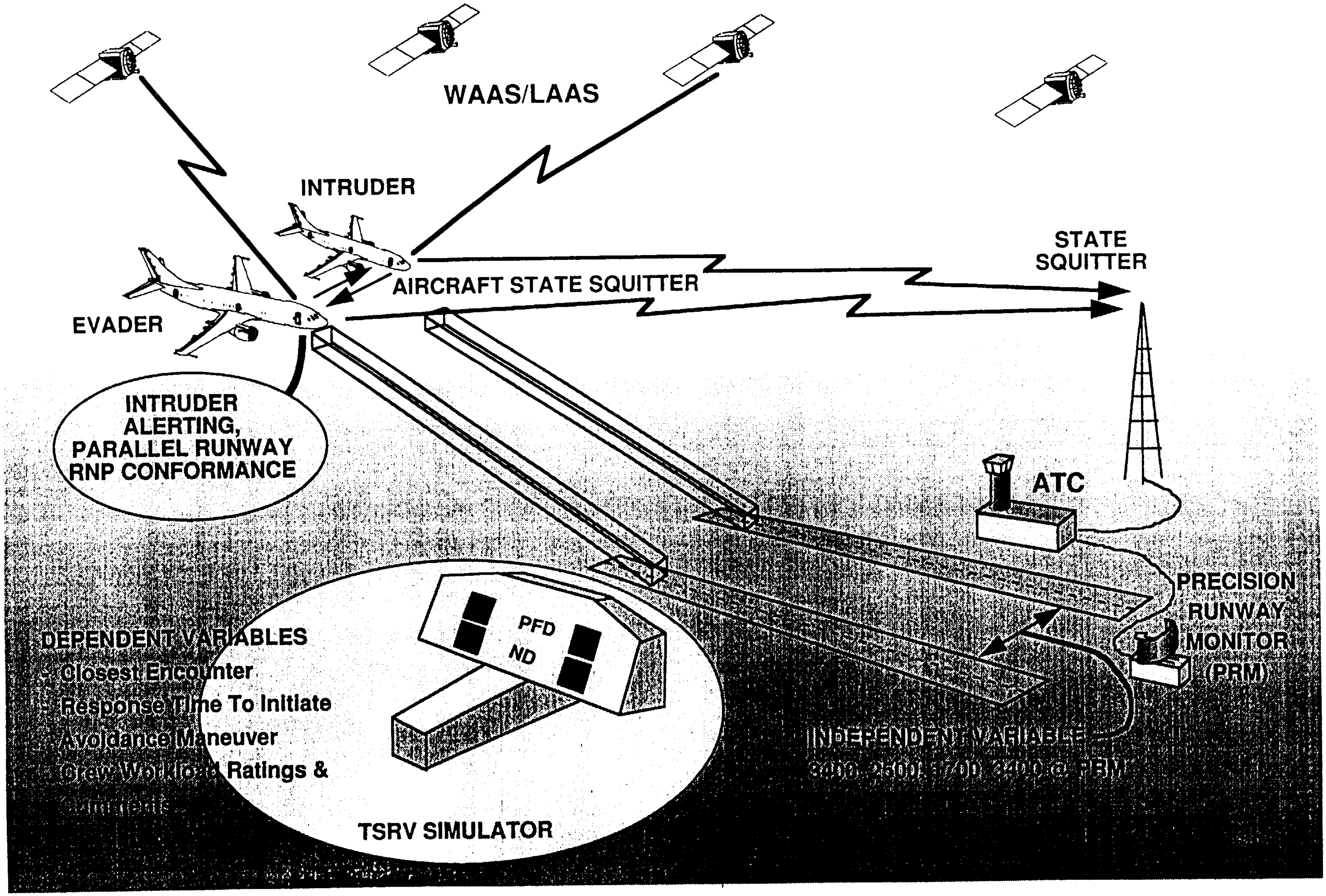


Figure 1-1 Airborne Information for Lateral Spacing (AILS) - System Concept

AILS Objectives and Goals

The following objectives/goals guide the development of the AILS system:

1) Achieve reduced runway spacings below those attainable by the PRM system through
   a) improved surveillance of aircraft intruder state and intent, providing reliable and timely alerts in the event a blunder occurs
   b) improved communication/provision of caution and warning alerts to flight crew
   c) development of a Parallel Approach RNP capability that provides high-integrity conformance to the parallel approach path.
2) Define information requirements for
   a) providing the intruder alerting function
   b) flight crew situational awareness and guidance
3) Define AILS flight crew procedures that
   a) reduce pilot response time in taking evasive action in the event of an intruder blunder
   b) do not add excessive additional workload to the flight crew during parallel approach operations.
4) Develop display formats that provide easily understood and discernible situational awareness and guidance to the flight crew.
5) Utilize existing and planned airspace infrastructure and capabilities, and avionics systems in order to minimize the cost of providing AILS parallel approach capability.
6) Provide display formats that allow transition from approach to taxi and surface operations.

AILS System Issues and Tradeoffs

A number of key issues and tradeoffs must be assessed and evaluated in the development of the AILS system. Many of these issues pertain to the alerting system, the role of displays (display formats) in providing the flight crew with appropriate situational awareness and guidance, and the type of evasive maneuver that is appropriate to avoid an aircraft collision incident. All of these are highly inter-related and require human factors and flight simulation evaluation to determine the appropriate level of flight crew - AILS system interaction.

A number of key questions must be answered:

1) What is the proper balance of full automation and rules versus human-in-the-loop judgment in detecting a threatening encounter and taking appropriate evasive action
2) Should simple displays be used, providing only level 3 alerts (alerts that require direct and unambiguous evasive action by the pilot), or should displays include additional information and formats that provide sufficient situational awareness and guidance for the pilot, for judgmental decision making on when an evasive maneuver is appropriate, and the extent of evasive maneuver that is needed to avoid an incident.
3) Scaling of display formats must balance the need for monitoring the entire approach path, while at the same time providing sufficient detail of AILS information on close-in parallel approach traffic and obstacles. Use of non-linear scaling to accommodate both aspects

requires human factors evaluation and flight simulation to ensure that display information matches pilot perception of the situation, is easily discernible and does not compromise the primary approach task (i.e., does not increase pilot workload during final approach).

The success of the AILS system concept for providing parallel runway approaches to closely-spaced runways depends entirely on the proper development of the surveillance/alerting function and on the ability of the system to allow for relatively short pilot response times in the event an evasive maneuver is required. Thus the above noted automation versus human-in-the-loop, and display format related issues are crucial to successful development of AILS.

Some other important issues to be addressed by the AILS system are:

1) AILS interface to Air Traffic Control in terms of communications and procedures in the event of an aircraft blunder during parallel approach operations.
2) The role and effect of wake vortex turbulence when runway spacings are reduced. At present, 2,500 ft lateral spacing is the lower limit for dependent parallel approaches [3]. As part of the TAP program, NASA is also addressing the wake vortex problem and plans to integrate solutions for lateral (AILS) and in-trail (wake vortex) reductions in aircraft separation.
3) Extent of pilot training needed to reduce response times to take evasive maneuver. There is also a training issue in performing a "break out" from final approach when coupled to the autopilot. "Break out" refers to taking evasive action during final approach.
4) For reduced runway spacings during parallel runway approaches, can aircraft be flown manually or will autopilot approaches be required to maintain reasonable flight technical error deviations? This must be addressed in the development of the AILS RNP sub-system.
5) Type of evasive maneuvers that will successfully avoid collision incidents. This is integrally tied to the AILS Alerting sub-system and also depends on aircraft performance characteristics.
6) In the event of a "break out" maneuver from final approach due to a blunder, the AILS system must ensure against obstacles (buildings, towers, mountains, etc.) in the break out path. This is likely airport dependent.
7) The impact of multiple parallel runways (more than two) on AILS must be considered. An evasive maneuver away from an intruder may adversely affect other traffic that may be performing a parallel approach near the "break out" path.
8) The interaction of AILS alerting with TCAS must also be addressed since both systems provide separation assurance in the airport terminal area. Ultimately AILS alerting could be viewed as an additional mode of TCAS that activates during approach and landing operations.
9) AILS alerting performance in terms of probability of missed detection of an actual blunder and the probability of false alarms is a key issue in the design of the alerting system in order to achieve the required level of safety of parallel runway approaches to closely-spaced runways.
10) Cost-benefits of AILS must be quantified.

AILS Team Research Activities - Overview

As indicated, the AILS program is part of NASA's Terminal Area Productivity (TAP) program and is led by NASA Langley and NASA Ames Research Centers. Other participant on the NASA AILS team are Lockheed Engineering Services, MIT and Collins Avionics. TAP program management is provided by NASA Ames with NASA Langley providing the technical leadership for AILS.

NASA Ames and MIT are addressing the human factors portion of developing AILS display formats. A number of displays and display formats are being considered that range from relatively simple displays providing level 3 alerts to more complex displays depicting greater pilot situational awareness and guidance allowing for more human-in-the-loop interaction. Studies include parallel approach simulations using subject pilots in part-task simulators that utilize a number of different displays. Subject pilots fly standard parallel approaches that are subjected to potential intruder blunders. The effectiveness of the various AILS displays and alerting criteria are evaluated by measuring the closest point of approach (CPA) that results due to a parallel approach blunder, by measuring response time of the AILS system and pilot in the event of a blunder, and by assessing the accuracy of the decision made by the subject pilot. Pilots are interviewed for subjective comments on the performance of the various display formats and system configurations.

Algorithms for the AILS alerting sub-system against intruder blunders are being developed by both MIT and Collins. This research will determine the minimum achievable runway spacings that can be supported by AILS. The close interaction between the role of AILS display formats and alerting criteria requires feedback of research results between AILS team members. Proper evaluation of the effectiveness of display formats and guidance cues is contingent upon the availability of appropriate alerting criteria. Conversely, the development of alerting criteria is also dependent upon pilot response time results from flight simulator experiments using appropriate display formats.

In addition to providing support in the area of AILS alerting, Collins is also involved in providing avionics support to the AILS team, both in terms of identifying avionics requirements for sensors and data communications needed by AILS, and in providing developmental avionics in support of flight test demonstrations of the AILS concept.

NASA Langley, with support from Lockheed Engineering Services, provides the overall technical lead for the AILS project, coordinating results of research from other AILS team members, and serving as system integrator in the development of flight simulator experiments and flight tests using NASA's B757 TSRV. This activity includes the selection of PFD and ND display formats for AILS, selection of AILS alerting criteria, and development of flight crew procedures for AILS parallel runway approach experiments. Display formats, alerting algorithms and flight crew procedures are integrated into the AILS flight simulator using NASA's B757 TSRV simulator.

AILS Status Summary of Current Activities and Future Plans

At this time, prototype display formats, alerting criteria and flight crew procedures have been developed and have been integrated in NASA Langley's TSRV flight simulator. Evaluation of the performance of this prototype AILS system using subject pilots is currently in progress.

While the initial AILS flight simulator experiment is in progress, research continues on the refinement of alerting criteria and on human factors studies on the impact of AILS display formats and displayed information on pilot performance. Improvements from these studies will be incorporated into future flight simulator experiments and flight tests. Results from the initial AILS flight simulator experiment will also provide useful feedback toward the development of display format, alerting criteria and flight deck procedures.

While to date the primary focus has been on the development of display formats and alerting criteria for the AILS (intruder) Alerting sub-system, the AILS team is also planning to address the AILS Parallel Approach RNP sub-system. This task involves the definition of a modified lateral approach path or tunnel that provides high-integrity aircraft RNP conformance to the specified containment boundary. Navigation and integrity monitoring system concepts will be developed to achieve this capability.

Appendix A provides additional information on the evolving AILS system concept as viewed by NASA's AILS team. Included in Appendix A is a guidelines document that has been adopted to direct the development of the AILS system (Table A-1). In addition, assumptions made in support of the current AILS flight simulator experiment are also documented (Table A-2). These are living documents that are periodically revised from lessons learned by the AILS team during the development of the system.

1.4 Organization of Report

In the previous section we have provided an overview of the NASA AILS system concept and AILS team activities and roles. The remainder of this report discusses results from Collins' study and development of AILS alerting criteria and examines avionics requirements needed to enable the concept. Section 2 discusses the development of a prototype AILS alerting system. An overview of alerting methodologies is provided, followed by a description of several candidate alerting algorithms. Section 3 describes the AILS simulation approach. Section 4 provides a top-level summary of AILS alerting performance, while section 5 examines AILS alerting sensitivities. Avionics sensor and data link communication requirements are presented in sections 6 and 7, respectively. Section 8 provides top-level airspace infrastructure requirements for AILS. Section 9 provides an assessment of NASA's TSRV avionics for AILS, and section 10 examines existing and evolving PRM techniques other than AILS and includes a cost comparison to AILS. A report summary and future plans are found in section 11.

Several appendices are also included. Appendix A summarizes AILS system guidelines and also provides a list of assumptions used in the initial flight simulator experiment of AILS. Analysis of Total System Error for ILS and GPS-based approaches are provided in Appendix B. Appendix C documents the flight track templates used in AILS alerting simulations.

2. AILS Alerting

This section provides an overview of the AILS alerting problem and examines alerting methodologies used in the development and evaluation of alerting systems. Candidate alerting algorithms developed for AILS are then described.

2.1 Overview of the AILS Alerting Problem

The goal of AILS is to allow reductions in runway spacings below 3,400 ft for independent parallel runway approaches during IMC. To achieve this goal, AILS must provide protection against incursion of an intruder aircraft into the path of the evader. It is widely held that the worst case blunder or aircraft deviation to be expected is a 30 degree standard rate turn by the intruder toward the evader's approach path [3]. This blunder scenario is shown in Figure 2-1 for an arbitrary runway spacing of 1,800 ft for an aircraft traveling at ~140 knots. Figure 2-1 indicates ideal surveillance updates by a PRM system using a 2.4 second update rate with the aircraft landing from right to left. It is evident that for this scenario only about 20 seconds transpire from blunder start to intercept of the evader's approach path.

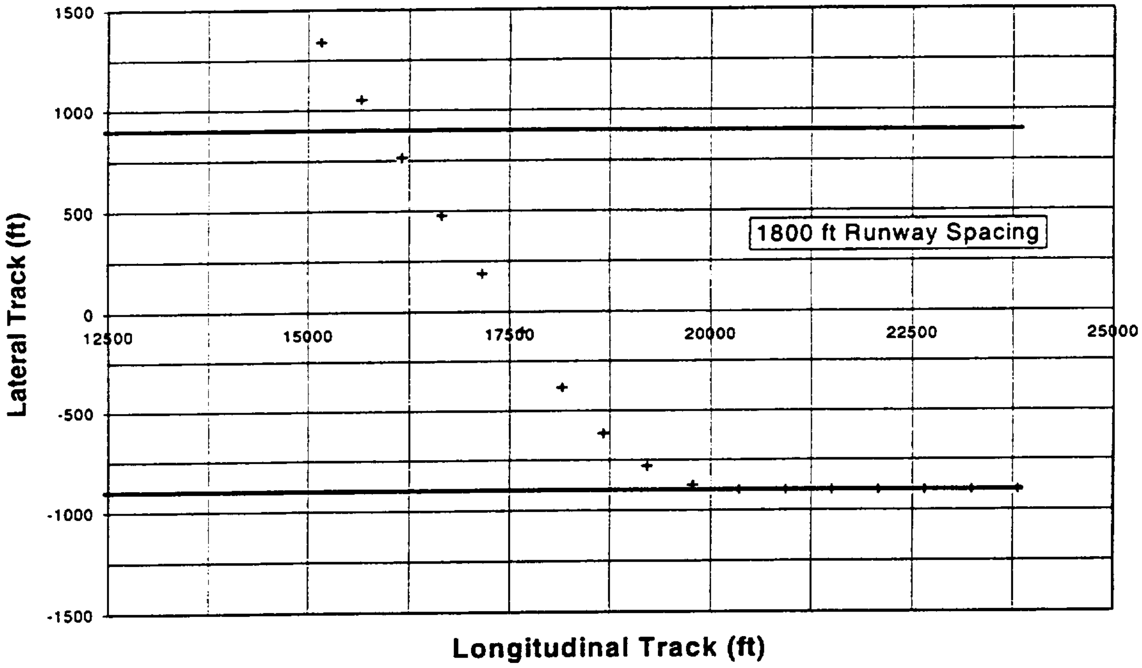


Figure 2-1 **Worst Case Blunder - 30 Degree Standard Rate Turn (2.4 sec PRM Updates)**

The challenge of any AILS alerting system is to provide timely and reliable caution and warning alerts. This entails accurate trajectory predictions of aircraft flight tracks in order to determine if a threatening situation is imminent. One difficulty with current Precision Runway Monitor (PRM) alerting concepts is that surveillance of aircraft tends to include appreciable time lags before it is recognized that a blunder has occurred. Current PRM systems utilize range and altitude surveillance replies and derive range rate and altitude rate from periodic updates. Due to measurement uncertainties, the alpha-beta tracking filters used for tracking aircraft range, range rate, altitude and altitude rate, and providing trajectory predictions provide considerable time lag in detecting an abrupt change in flight path. Even for ideal surveillance updates and accuracy, range rate reacts relatively slow when detecting a 30 degree blunder and does not indicate the full extent of a blunder until a considerable amount of time has transpired. Other trend predictions based on pure heading projection also provide substantial time lags as illustrated in Figure 2-2. Figure 2-2 compares the actual track to a predicted 10 second heading track.

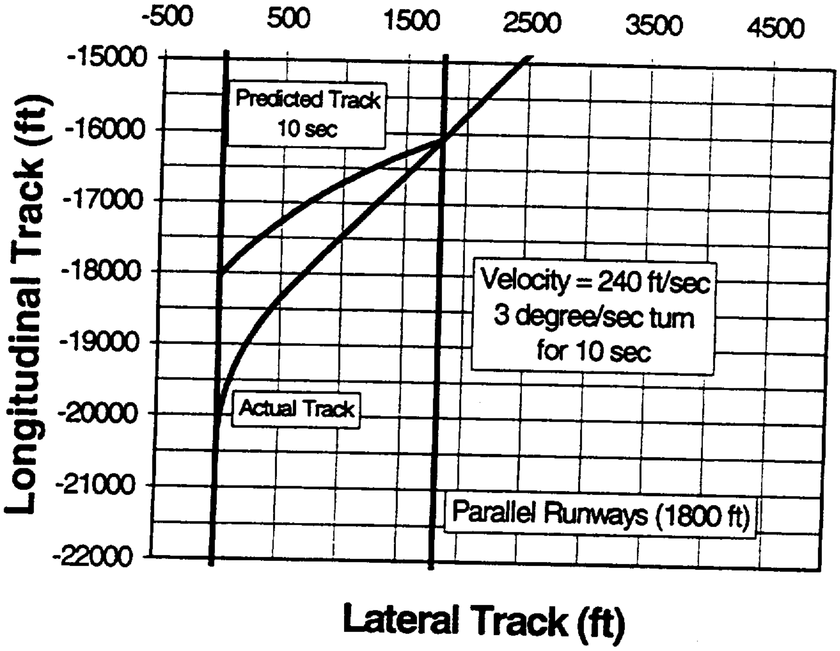


Figure 2-2 **Actual and Predicted Flight Tracks - 10 Second Heading Prediction**

In order to compensate for excessive time lags when detecting aircraft blunders, any alerting system must expand the protection volume, or conversely, increase the prediction time to ensure adequate alerting performance (i.e., low probability of missed detection, P_{MD}, and low probability of false alarms, P_{FA}). When time lags are excessive and alerting performance is relatively poor for a particular runway spacing, the only choice is to further increase the allowable runway spacing to ensure safety.

Before exploring candidate alerting algorithms for AILS it is appropriate to take a closer look at alerting system methods.

2.2 Alerting System Development and Evaluation Methodologies

A good description of alerting systems and methodologies for evaluating them is provided by Kuchar and Hansman from MIT [4]. This report addresses the modeling of alerting systems in "state space", which has the potential advantage of allowing a closed-form analytical approach to be used to evaluate an alerting system. The individual state variables represent parameters that define the dynamics of the hazard situation, e. g., relative position, velocities, etc., for a collision avoidance system.

Much of the focus of developing an alerting system is in the prediction of the future trajectory of aircraft tracks. By monitoring and projecting aircraft tracks, and being aware of the hazard location or region, a system can be designed to provide alerts in the event "hazard space" is encountered. To allow margins for aircraft maneuverability, hazard space is extended to "maneuver limit space" and is further extend to an "alert space" since it is unrealistic to expect limit maneuver performance in the event of an alert.

A system that is designed to avoid "alert space" may have an alerting curve as shown in Figure 2-3. Figure 2-3 shows the probability of an incident (i.e., collision or near miss) given the observed state measurement (y) along the projected flight track trajectory (T), i.e., $P_T(I \mid y)$. The probability of an incident is cumulative and is 0 at the far left and 1 at the far right of the curve. Four different alerting outcomes are possible as depicted in Figure 2-3. To the left of the alerting threshold are the regions P(TN) and P(FN), which represent the areas of True - Negative and False - Negative, respectively. Negative refers to the fact that no alert was issued, True implies that the correct decision (alert or no alert) was made and False implies that the wrong alerting decision was made. P(TN) thus represents the probability of correct non-detection and P(FN) represents the probability of missed detection. To the right of the alerting thresholds, i.e., an alert is issued, P(TP) represents the probability of correct detection of an incident and P(FP) represents the probability of a false alarm.

The goal of an AILS alerting system is to achieve a low probability of missed detection, P_{MD} (or P(FN)), and at the same time have a low probability of false alarms, P_{FA} (or P(FP)). As seen from Figure 2-3, in order to achieve these goals the probability of incident curve as a function of the measurement state(s) must be relatively steep, otherwise it becomes impossible to achieve both, low P_{MD} and low P_{FA}. A better illustration of this tradeoff is shown in Figure 2-4, which illustrates the relationship of P_{MD} versus P_{FA}. The upper curve represents the probability of an incident given no alert was issued and subsequently no evasive action was taken. The lower curve represents the probability of an incident when an alert was issued and evasive action was taken. The difference between the two curves shows the benefit obtained by the alerting system; P_{MD} is set by the lower curve and P_{FA} is determined by the upper curve.

Figure 2-5 shows the System Operating Characteristic (SOC) curve that results from the thresholds in Figure 2-4. An ideal alerting system would exhibit an SOC curve that reaches the upper left-hand corner, providing a 100 % probability of correct detection, P(CD), with 0 % false alarms, P(FA).

The steepness of the alerting curve is primarily affected by two factors: 1) selection of state variables that model the dynamics of the system, and 2) measurement accuracy of state variables. Improper selection, or lack of observable state variables will result in a poor alerting system.

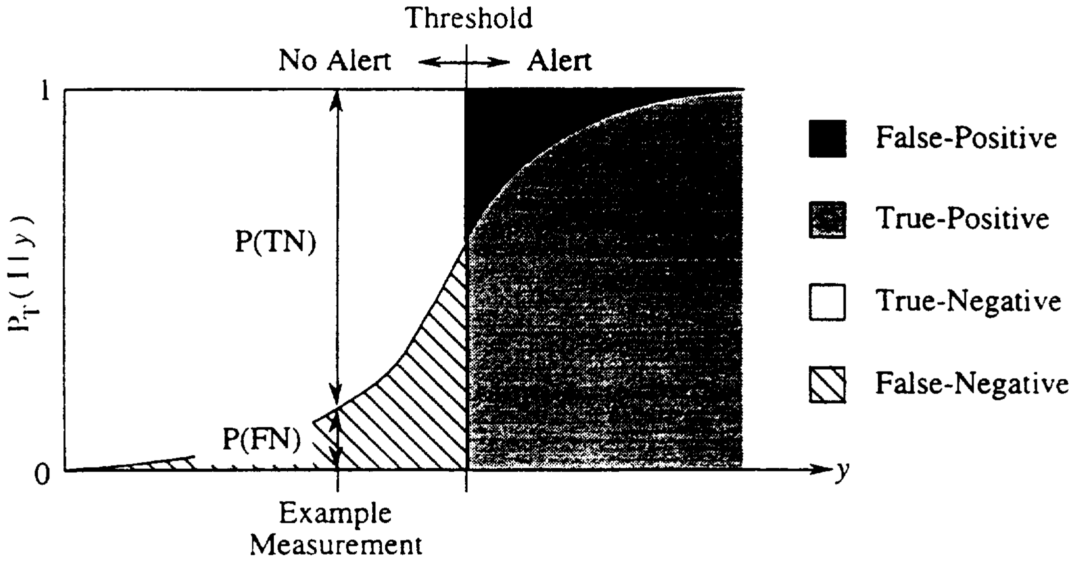


Figure 2-3 Alerting Decision Outcomes - Example $P_T(I \mid y)$ With Alerting Threshold

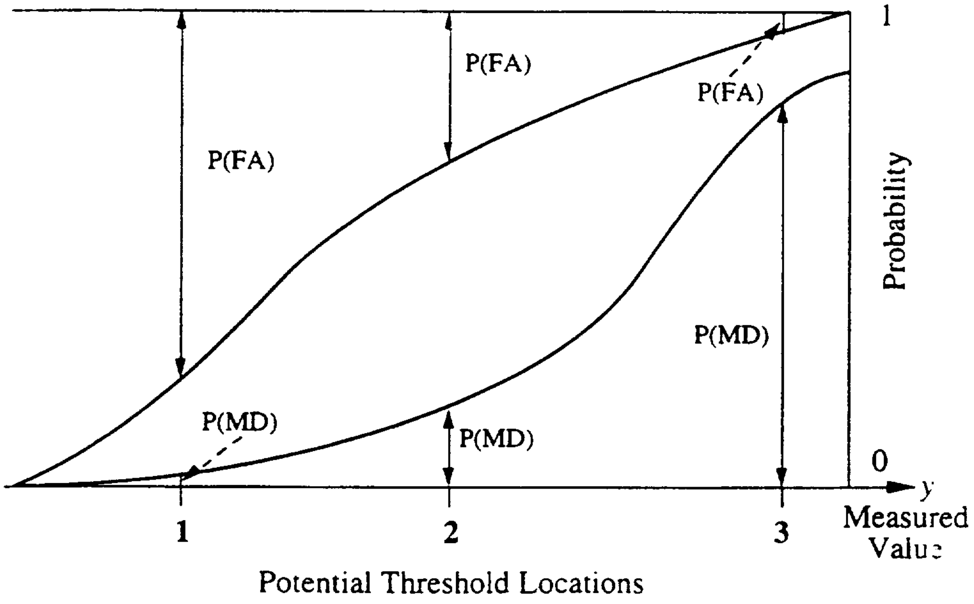


Figure 2-4 Relationship Between Alerting Threshold Location and P(FA) and P(MD)

Reference [4] suggests a closed-form equation for evaluating the effectiveness of an alerting system by allowing computation of $P_{incident}$. If one is able to determine the probability density functions (PDFs) associated with the uncertainties in aircraft state-space representation, and the range of possible aircraft trajectories that may be traversed by both aircraft, then the methodology allows computation of $P_{incident}$ using a closed-form numerical integration of these over the exclusion zone, which is the region of state-space where the aircraft protective volumes encroach/collide with each other. The challenge is thus to determine the correct PDFs associated with aircraft state variables and state trajectories. For the AILS problem, this appears to be a very difficult task.

An alternative approach to closed-form analysis is the use of Monte Carlo simulation of parallel runway approaches. This approach, given a sufficient number of random trials, provides an indication of the performance of an alerting system. Parallel approach scenarios must of course provide a good representation of the statistical variations associated with surveillance errors, update rates of data, and the various response times and latencies associated with the AILS system.

Monte Carlo simulations have been used in previous parallel runway alerting evaluation studies [1][3]. This study also resorted to the use of Monte Carlo simulation to evaluate candidate AILS alerting algorithms. The approach will be discussed later in this section.

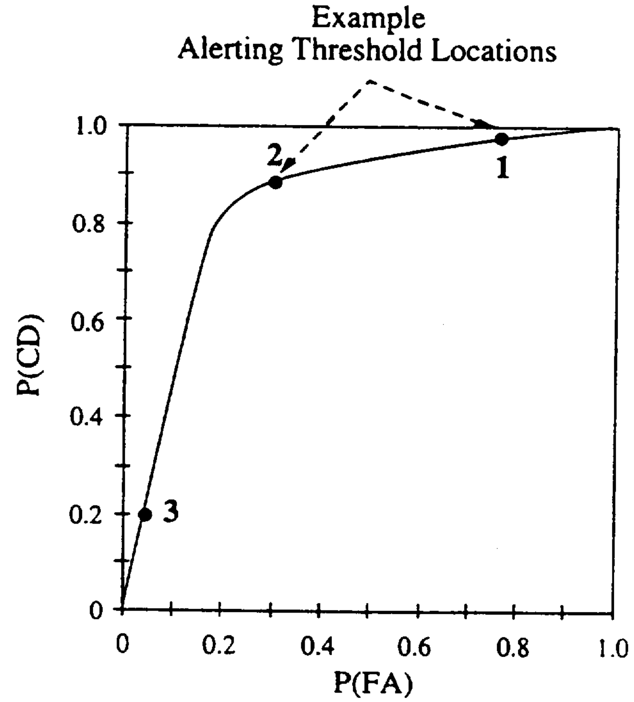


Figure 2-5 System Operating Characteristic (SOC) Curve

2.3 Current Parallel Approach Procedures - Scope of AILS Alerting System

To illustrate the scope of AILS alerting, this section provides a brief overview of the approach and landing flight phases as they pertain to independent parallel runway approaches.

The transition from the enroute to the approach flight phase typically occurs at the last waypoint in the flight plan, which is approximately 25 nmi from the airport. At this point the aircraft enters the designated STAR (standard arrival route) to proceed toward the airport. In the vicinity of entering the STAR, ATC typically makes contact with the aircraft and begins to issue heading vectors and altitude assignments to be followed. ATC vectoring instructions are highly variable (in frequency and path) from airport to airport and likely vary for the same airport depending on traffic load and weather. Vectoring instructions are currently issued via voice communications, but may be sent via data link in the future.

Separation assurance during this phase of flight is provided by ATC with TCAS serving as a back-up.

ATC continues to vector the aircraft toward the final approach path. The last vector instruction from ATC is for the aircraft to "intercept" the final approach path at a designated altitude. Currently in IMC conditions, the aircraft is "turned on" to the localizer path, with an intercept angle of 30 degrees or less with a minimum of 1,000 ft altitude separation to other aircraft on parallel approaches.

Figure 2-6 illustrates the vertical approach profile for parallel approaches during IMC. As indicated, during intercept of the localizer, aircraft on parallel approach maintain a minimum of 1,000 ft of altitude separation. Approaches are paired at either 3,000 ft / 4,000 ft or 2,000 ft / 3,000 ft altitudes above ground level. At these altitude pairs, aircraft abeam of each other achieve co-altitude at approximately 9 nmi and 6 nmi, respectively. Clearly, by the time co-altitude is reached, it is imperative that both aircraft are "established" on the localizer path, i.e., lateral deviations that may have been as much as +/- 3,000 ft during localizer intercept are now reduced to within typical lateral errors during final approach.

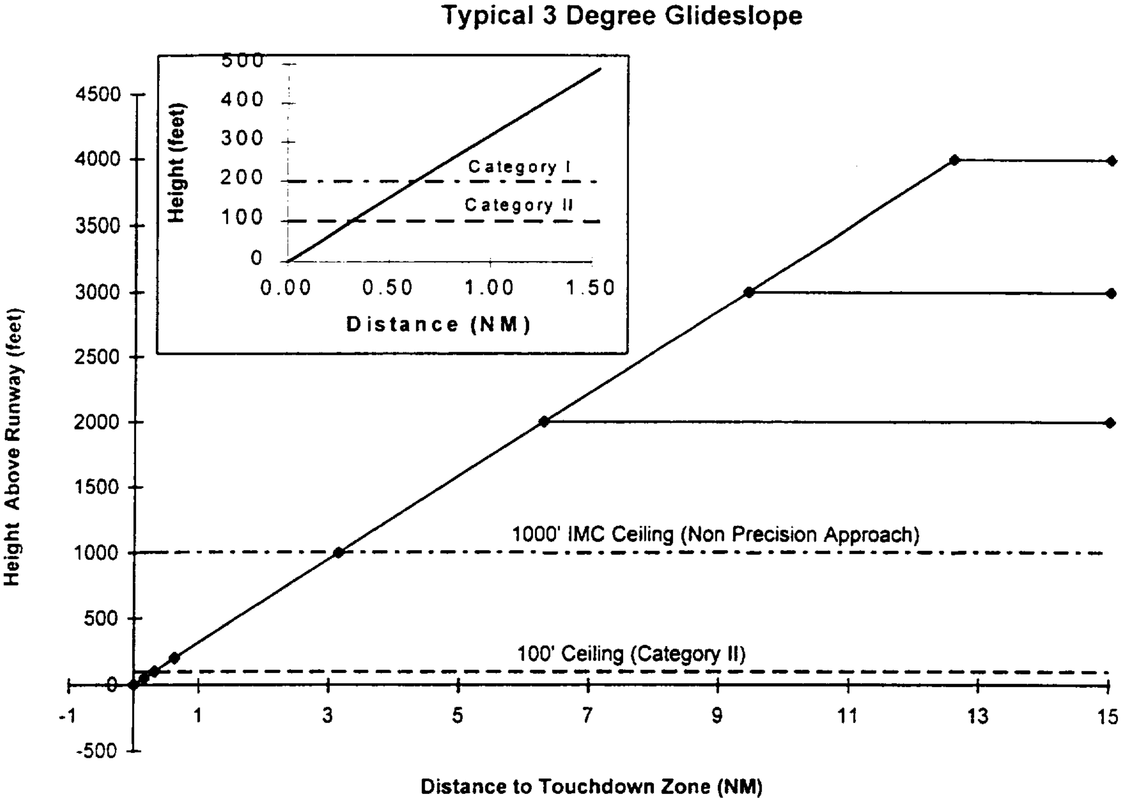


Figure 2-6 Vertical Approach Profile for Independent Parallel Runway Approaches

Transition from TCAS to AILS separation assurance likely will take place late in the localizer "turn-on" phase or early in the localizer "establish/stabilize" approach phase. TCAS and AILS alerting functions may actually be active simultaneously for some duration to provide some overlap in separation assurance. Needless to say, the "turn-on" and "establish/stabilize" phases pose challenging separation assurance requirements. TCAS for instance has difficulty in dealing with two-aircraft involved in turning on to the approach path due to their relative close proximity and turning maneuvers. TCAS alerting thresholds are intentionally less sensitive in this flight phase to avoid excessive false alarms while still providing separation assurance. It is therefore vital that current localizer intercept and altitude separation standards and procedures for independent parallel runway procedures continue to be utilized in the AILS environment.

From the perspective of this study, the focus of AILS separation assurance / alerting begins once both aircraft are established/stabilized on localizer and continues through landing, and perhaps through the early part of a missed approach. A secondary issue not addressed in this study is the TCAS/AILS alerting interface during runway intercept and during the later portions of a missed approach.

Note: Current independent parallel runway approach procedures are defined in the FAA's Airman's Information Manual [5].

2.4 Development and Evaluation of AILS Alerting Algorithms - Approach

The approach followed in developing and evaluating AILS alerting algorithms is as follows:

1) Identify aircraft state variables and possibly intent information that may be used to track the aircraft state trajectories and to develop trend vector predictions leading to alerting criteria.

   Candidate state variables are position (range and altitude) and velocity vectors for both aircraft which are derived from on-board sensors and ADS-B GPS position reports. Bank angle of the intruding aircraft is expected to be an important state variable, leading to early detection and prediction of aircraft blunders. Ground track and ground speed state information for the intruding aircraft will be required if circular path trend vector prediction is utilized. This is based on the relationship, $R = V^2/(g * \tan(\phi))$, where R is the radius of the coordinated turn, V is the aircraft ground speed, ϕ is the bank angle, and g is the gravitational acceleration constant. This information may be received directly from the intruding aircraft via data link or may be computed from ADS-B position reports.

2) Develop prototype alerting criteria.

   Once state variables are identified, prototype alerting algorithms will be developed that track and predict future aircraft trajectories based on aircraft state information. The success of these algorithms will depend on their ability to match predicted flight trajectories to the trajectories of actual blunders.

   Alerting algorithms that are based strictly on relative range and range rate between aircraft will likely provide inadequate (late) detection of a 30 degree blunder. This is due to the fact that these state variables change only slowly in the early stages of such a blunder. By including other aircraft state and intent information, such as intruder bank angle, it is expected that an early blunder indication and improved trend vector prediction will be possible.

For the prototype alerting algorithms, the prediction time factor, analogous to TAU used in TCAS, must be commensurate with the sum of all AILS system response times and latencies to allow sufficient warning for an evasive maneuver to take place. AILS system response times consist of delays associated with sensors, data link, alerting computation, display processing, and pilot / aircraft response time to AILS alerts.

3) Develop aircraft tracks for later use in Monte Carlo simulations.

   a. Select blunder scenarios to be evaluated.

      As indicated earlier, the 30 degree blunder represents the worst case blunder scenario, previously considered for evaluation of FAA's ground-based PRM system [3]. The 30 degree blunder is a very aggressive and perhaps unrealistically severe blunder scenario, which will place a substantial burden on any alerting algorithm. It is considered in this study to allow comparison to the FAA ground-based PRM system. Other blunder scenarios to be considered are less aggressive blunder turns and slow drifts off course by the intruding aircraft toward the evader's runway. For this study focus of blunder scenarios is confined to lateral blunders only, that occur once both aircraft are established on localizer. Altitude blunders have a more pronounced effect during aircraft turn-on to localizer, and are not considered in this initial development of AILS alerting criteria. Missed approach blunders will also be deferred for later evaluation.

   b. Characterize Total System Error (TSE) / Flight Technical Error(FTE) experienced by aircraft on final approach.

      An assessment of typical cross-track / lateral errors for normally completed approaches and landings is required. ILS and GPS-based approaches for both manual and autopilot approach / landings will be considered.

   c. Generate aircraft tracks for both aircraft (intruder and evader aircraft). These tracks will serve as templates for developing the large pool of track pairs needed for Monte Carlo simulation of AILS alerting.

      Intruder tracks will be limited to a few template blunder scenarios, which exhibit various degrees of "severity" or "aggressiveness" in terms of turn rate and heading blunders.

      Only a few evader aircraft track templates are needed in order to emulate normal approach scenarios.

      In addition to the above mentioned "normal" tracks for the evader aircraft, several evasion maneuvers will be generated, which exhibit various levels of pilot "aggressiveness" in taking evasive measures. These evasive maneuver segments will be overlaid on the "normal" evader tracks during Monte Carlo simulations once an AILS alert is issued. The evasive maneuver is activated once the prescribed pilot / aircraft response time delay has expired.

d. Determine statistical distributions to be used for Monte Carlo simulations.

Statistical distributions (PDFs) must be obtained for several parameters:

- Cross-track displacement of flight track templates (developed in the previous step) during track initiation, reflecting TSE and Flight Technical Errors (FTE).
- Longitudinal track displacement of flight track templates between evader and intruder aircraft to simulate the range of all possible geometries (intruder ahead or behind evader using random distributions). A uniform distribution of offsets will be assumed. The range of the distribution will be on the order of +/- 1.5 nmi.
- Blunder start location.
- Pilot and aircraft response times to actuate an evasive maneuver to an AILS alert. A distribution of response times will be determined. Initially, response times obtained by the FAA PRM program may be used (pilot and airplane generally responded within 15 sec of an alert), until data becomes available from NASA's live flight simulator tests of the AILS system. These response times will be used to delay the overlay of evasive maneuver tracks on top of the normal evader track being used.

4) Develop the APRM simulation program.

This activity involves the design and coding of the actual simulation program that will perform the Monte Carlo evaluation of prototype AILS alerting algorithms.

5) Perform Monte Carlo simulations.

Monte Carlo simulations will be run for the various blunder scenarios using the aircraft track templates obtained previously. The simulation will exercise the various probability density functions for cross-track and longitudinal track offsets, blunder start, the range of ground speeds of each aircraft, and pilot/aircraft response times. The output of the simulation will be the probability of missed detection and probability of false alarms, and an indication of closest point of approach (CPA). An incident is defined as a CPA of 500 ft or less. Other independent variables to be considered for analysis are runway spacing, blunder type, number of track pairs to be simulated, alerting thresholds (forward prediction time, $t_{predict}$, similar to Tau used in TCAS; protection volume threshold), type of evasive maneuver, data uncertainty and data update rate.

2.5 Candidate AILS Alerting Algorithms

Several candidate AILS alerting algorithms were developed and evaluated. Some preliminary alerting results influenced the development of these algorithm based on the relatively quick response of trajectory predictions when using intruder bank angle.

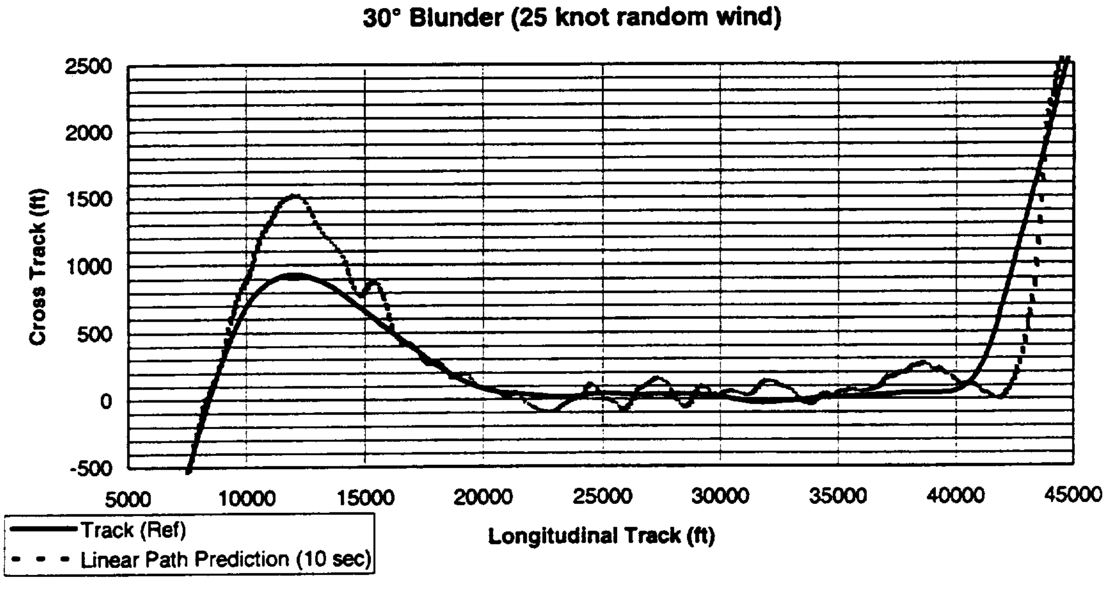
The use of bank angle as a new state variable to be considered in AILS alerting is motivated by the recognition that current PRM alerting systems have relatively poor response times due to the slow response of range, range rate and heading state variables to high dynamic rate blunders. As stated previously, the proper modeling of dynamics using aircraft state variables is vital in the development of good alerting systems, i.e., relatively steep probability of incident curves as a function of the measured state variables (refer to Figures 2-3, 2-4 and 2-

5). Some other detracting characteristics in current PRM alerting systems are: 1) differentiation noise associated with the computation of range rate from periodic range surveillance replies, limited update rate and accuracy of surveillance data, and the time lag associated with alpha-beta tracking filters due to noisy inputs.

Figures 2-7 and 2-8 illustrate preliminary alerting results for a typical 30 degree worst case blunder using trajectory predictions based on heading and bank angle (i. e., a circular path, constant radius turn), respectively for an arbitrary 10 second prediction time. These figures depict the standard 30 degree intercept of localizer (left side of diagram), which includes an appreciable overshoot during initial acquisition of localizer. The aircraft then begins to become "established" on the localizer as it continues the approach from left to right. The approach continues until the occurance of the 30 degree blunder. As indicated in these figures, the circular path prediction requires only 2.3 seconds to project the blundering aircraft into the 600 ft Non-Transgression Zone (NTZ), while the heading path prediction takes 5 seconds. The oscillations observed in the respective predicted trajectories are the result of wind induced variations in aircraft ground track heading and bank angle.

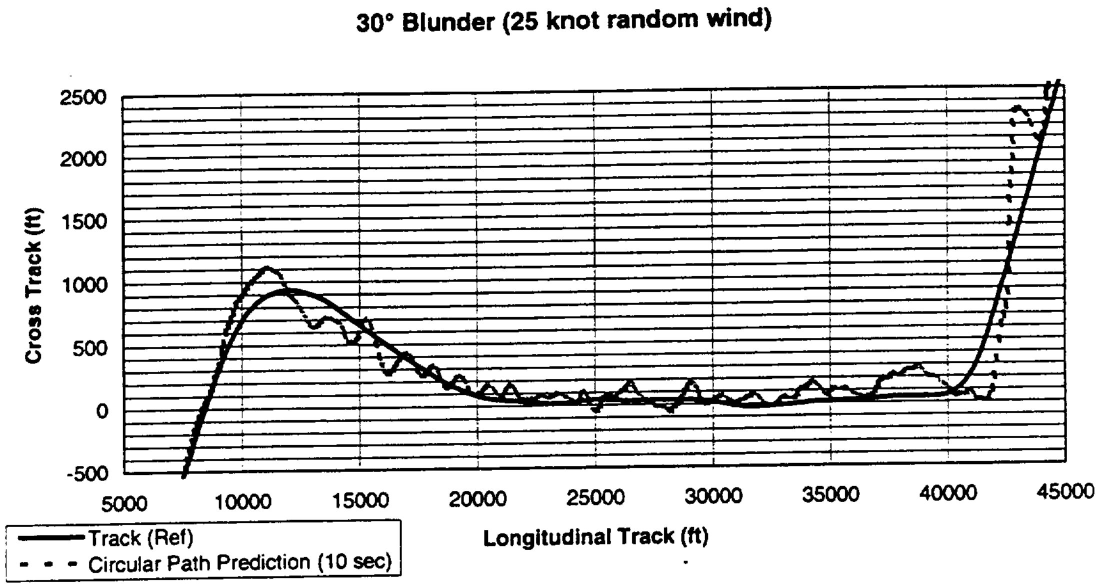
Note: The NTZ alert detection criterion used here was only to allow simple demonstration of the relatively aggressive prediction made possible by using bank angle. AILS alerting algorithms to be discussed next do not utilize the NTZ alerting concept but instead use the concept of an alerting bubble about each aircraft that protects against collisions and near misses, i. e., CPA of less than 500 ft.

The following sections present the AILS alerting algorithms that were developed and evaluated.



Detection Time (t_{detect} - $t_{blunder}$) = 5.0 seconds (600 foot NTZ)

Figure 2-7 Preliminary Alerting Using Ground Track Heading Prediction



Detection Time (t_{detect} - $t_{blunder}$) = 2.3 seconds (600 foot NTZ)

Figure 2-8 **Preliminary Alerting Using Circular Path Prediction (Bank Angle)**

2.5.1 AILS Circular Alerting System (Algorithm)

For the circular alerting system, the aircraft is assumed to make a constant bank turn at its current observed bank angle, (see Figure 2-9). At each sample instant, a new trajectory is generated. Two parameters are computed to determine if an incident is likely; the predicted time to when the intruder intercepts the invader's path, and the distance between the two aircraft at the intercept point.

If the time to intercept is less than a threshold (time threshold) and the long track distance between the aircraft at intercept is less than a threshold (warning threshold), the system indicates that an incident is likely to occur and a warning is issued. The threshold settings determine the false alarm (FA) and missed detection (MD) rates. Clearly, low FA and MD rates are both desirable. However, both may not be possible depending on the alerting system and the selection of threshold levels. By changing the thresholds, system trade-offs between FA's and MD's can be made. The time threshold is somewhat constrained since it must account for all of the latencies associated with the detection of an intrusion and the subsequent evasion maneuver, i.e. the pilot/aircraft response time and the time required for the evading aircraft to perform the evasive maneuver. Twenty seconds has typically been used as a first approximation of these time latencies.

For circular alerting, only one trajectory per sample is used to determine if an incident is likely. If the bank angle has large fluctuations, the predicted trajectory can change significantly from instant-to-instant. In turn, a noisy predicted trajectory can greatly effect the accuracy of the alerting decision and can result in a potentially high false alarm and/or missed detection rate. Figure 2-10 shows several successive circular predictions for the 30° heading

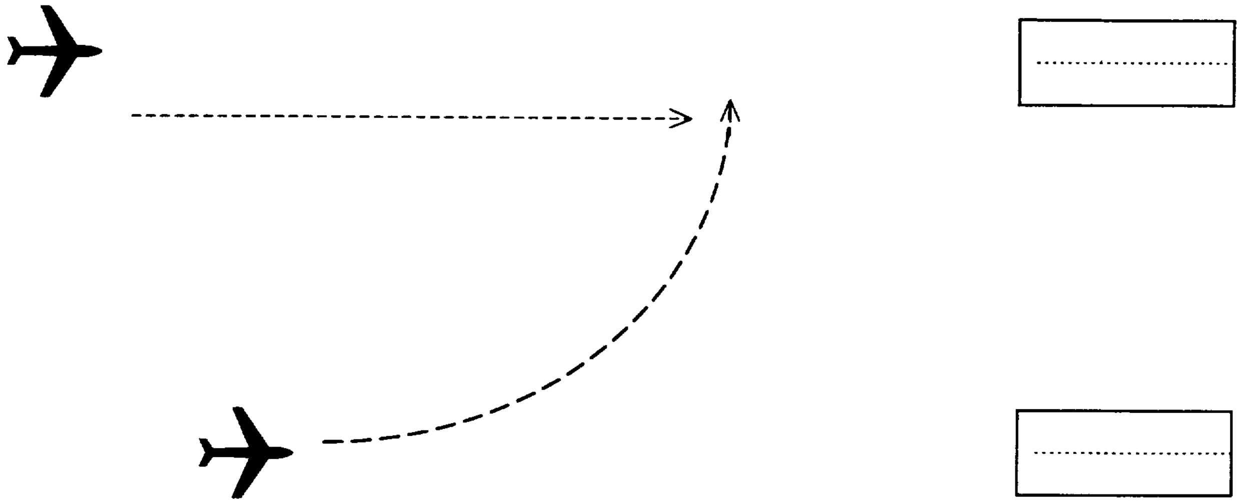


Figure 2-9 Constant Bank Turn Assumption for Circular Alerting

blunder. In this figure, the dark line is the actual flight path flown by the intruder and the dashed lines are predictions computed from four successive bank angle measurements taken along the flight path. The family of predicted paths show a time sequence of projections as the aircraft's bank angle changes over time (four different times). Note that the predictions are based strictly on the intruder's bank angle and are independent of the evader's position. For each bank angle sample the predicted path either hits or misses the evader aircraft. For large bank angle fluctuations, this method leads to spurious predictions and adversely effects false alarm performance. The next section describes "segmented alerting" which attempts to reduce the effect of bank angle fluctuation on alerting performance.

2.5.2 AILS Segmented Alerting System (Algorithm)

Like the circular approach, the segmented altering system assumes that the intruder performs a coordinated turn at the measured bank angle. In addition, the segmented prediction allows the intruder to roll out at several headings along the turn trajectory and follow a straight flight path (Figure 2-11), hence the "segmented" name for the two segments of the predicted trajectory. Thus, for each bank angle measurement the intruder prediction could follow one of several assumed flight paths. The predicted trajectories shown in Figure 2-11 represent several possible flight paths the intruder "may" follow. These trajectories are computed on a single measurement update of the intruder bank angle and heading. The flight path that is most likely to cause an incident in the least amount of time is used to determine if a warning is issued. If the time to intercept of the selected path is less than a threshold and the long track distance between the aircraft at intercept is less than a warning threshold, the system indicates that an incident is likely and a warning should be issued. Using the segmented technique, the alerting system is adaptive to the position of the evading aircraft.

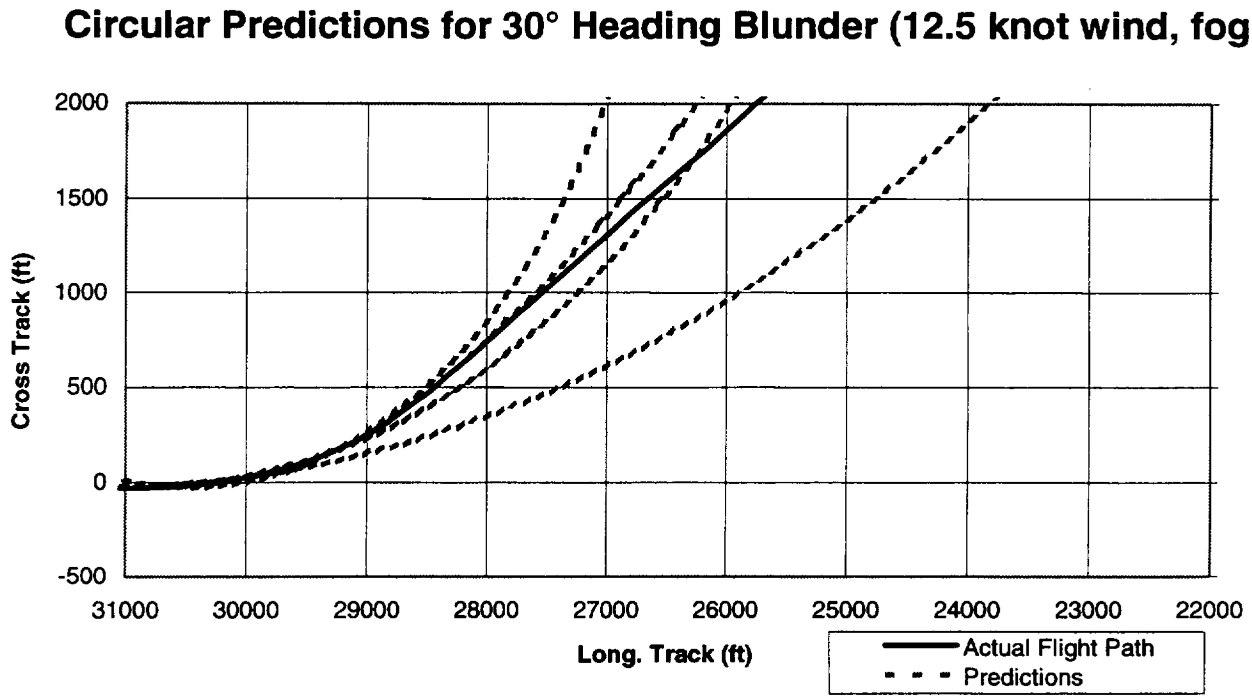

Circular Predictions for 30° Heading Blunder (12.5 knot wind, fog)

Figure 2-10 Successive Circular Alerting Predictions for a 30° Blunder

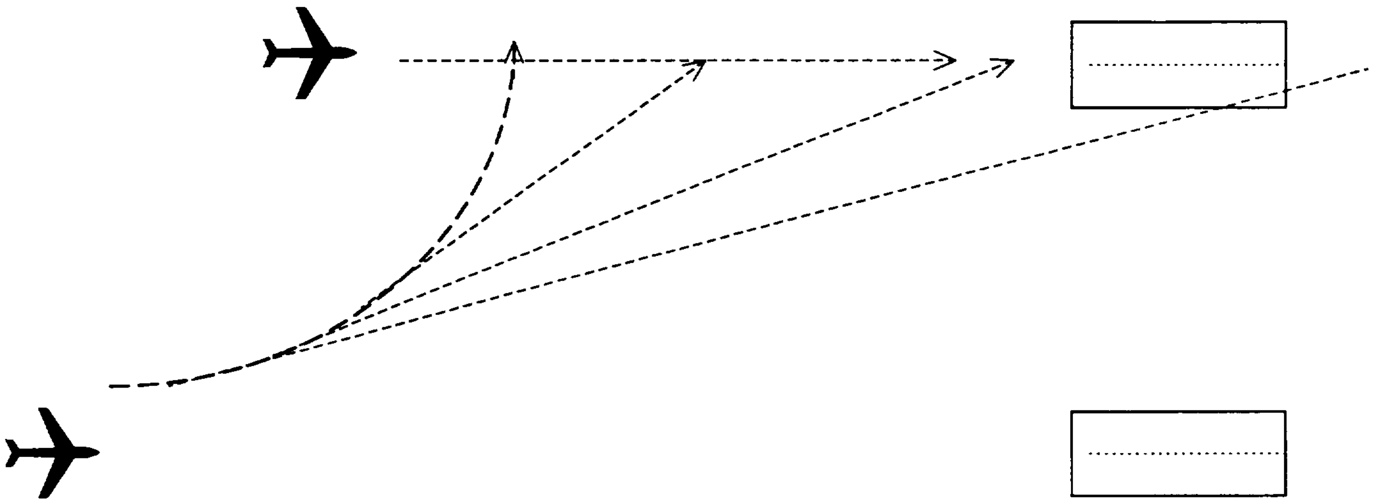


Figure 2-11 Several Potential Flight Path Predictions for Segmented Alerting

Several prediction scenarios are shown in Figures 2-12 to 2-14. As before, the dark line represents the actual flight path flown by the intruder and the dashed lines are predictions computed from four successive bank angle measurements taken along the flight path. The family of predicted paths show a time sequence of worst-case projections as the intruder's bank angle changes over time (four different times).

Assuming the evader's runway is at 2,000 ft cross track, Figure 2-12 shows the predictions when the own aircraft is projected to be at 26,000 ft long track when the intruder crosses the evader's runway. Clearly, for an own aircraft at 26,000 ft long track the actual flight path of the intruder represents a threat. The majority of predictions fall very close to the evader's position and warn the evader aircraft in enough time for an evasive maneuver.

Figure 2-13 shows the predictions when own aircraft is projected to be at 25,000 ft long track when the intruder crosses the evader's runway. Again, several of the predictions are directed at the evader's predicted position. Since we do not actual know the intruder's flight path when the predictions are made, a warning must be issued if the time required for the intruder to reach own aircraft is less than the latencies required for an evasive maneuver. With a majority of the predictions directed at own aircraft, there is better opportunity to detect threatening situations more quickly. In contrast, none of the predictions of the circular alerting system would provide an indication of a threatening condition when own aircraft is projected at 25,000 feet long track (refer to Figure 2-10).

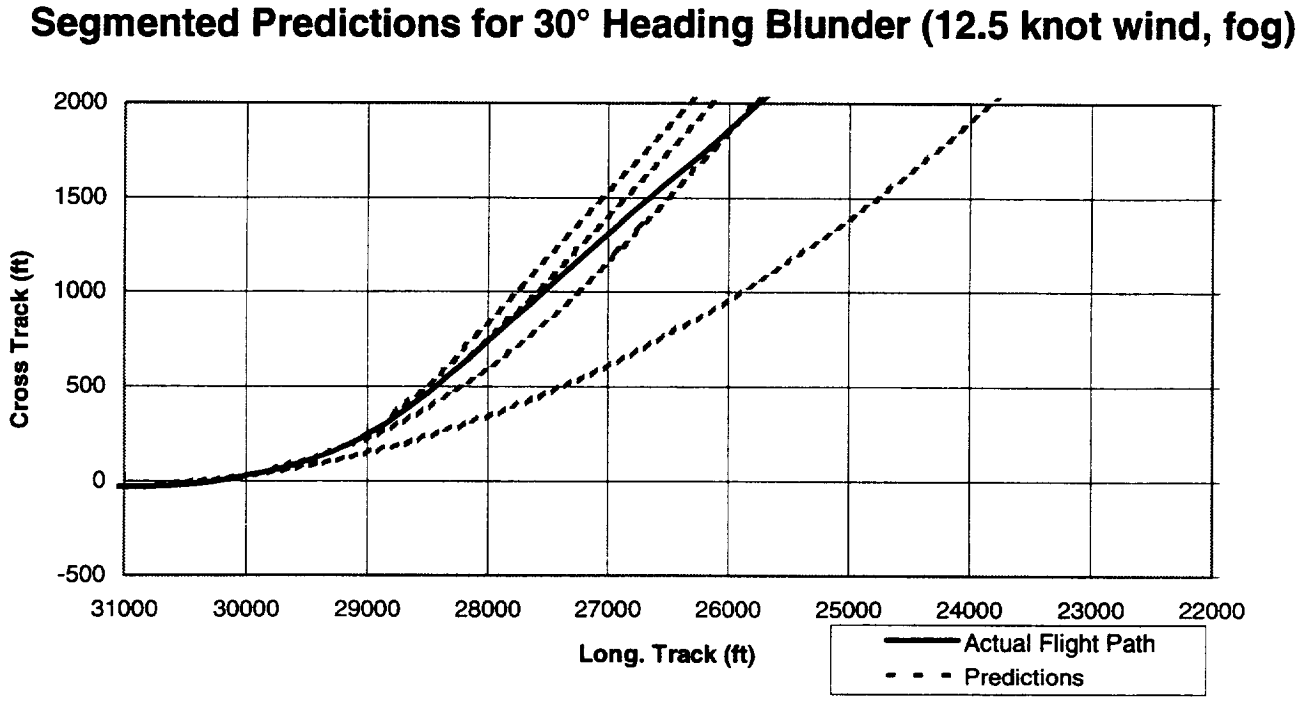


Figure 12 **Segmented Predictions (Evader Aircraft Predicted at 26,000 feet Longitudinal Track)**

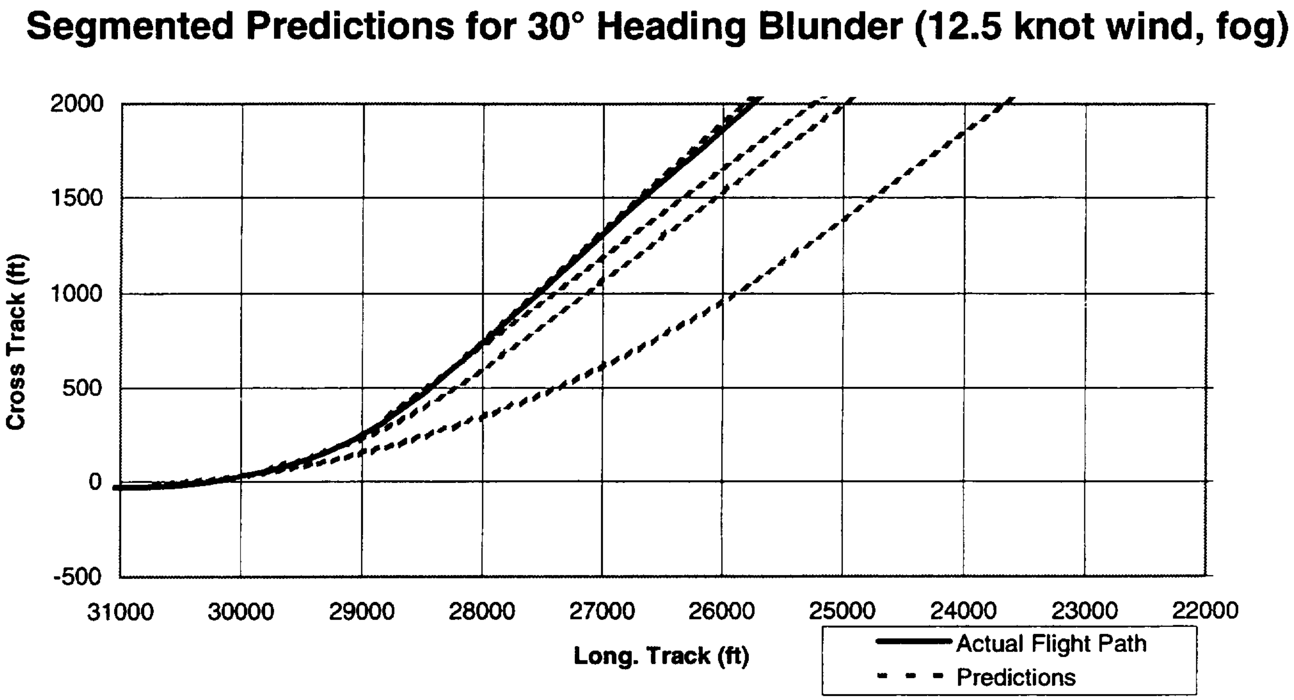


Figure 2-13 Segmented Predictions (Evader Aircraft Predicted at 25,000 feet Longitudinal Track)

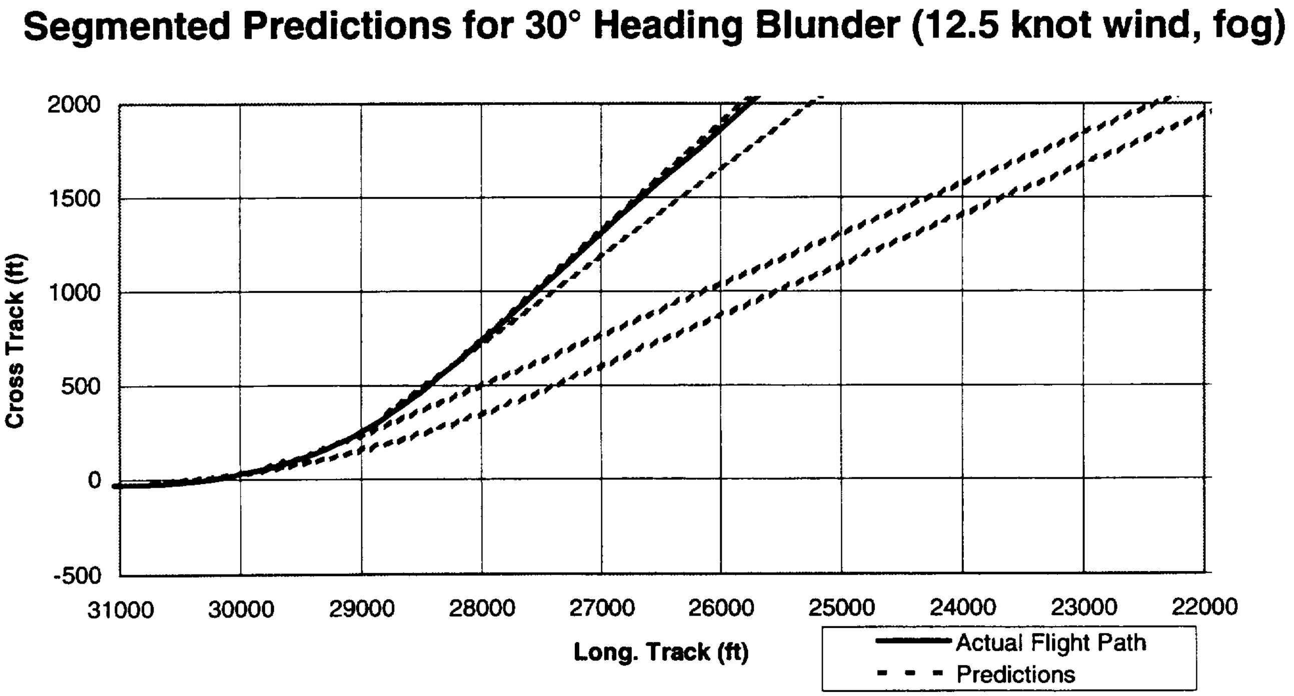


Figure 2-14 Segmented Predictions (Evader Aircraft Predicted at 22,000 feet Longitudinal Track)

A final example of segmented alerting prediction projects own aircraft at 22,000 ft (Figure 2-14). In this case predictions directed at own aircraft represent a relatively long period of time (long distance) and, thus a warning would not be issued. Notice that two of the predictions are not directed at the evader's predicted position. At the time these predictions where made, the alerting system determined that the intruder was not able to reach the evader's predicted position at its measured bank angle and heading.

As indicated in the examples above, by directing predictions to where they represent the greatest threat to own aircraft, the segmented alerting system should be able to detect blunders more quickly than the circular approach.

While the early detection of blunders is a desirable trait of segmented alerting, a potential concern for this method is the possibility of higher false alarm rates. This concern arises from the fact that predictions are focused on own aircraft solving for the worst case scenario, these being vulnerable to move frequent warnings. Based on simulation results (section 4), the concern about excessive false alarm rates for the segmented alerting system were unfounded. In fact, segmented alerting provided the best false alarm performance of all alerting systems. It appears that predictions based on segmented alerting provide a good match to actual intruder flight paths and are quite accurate. This is reflected by the fact that most false alarms fall within 1,000 feet of own aircraft.

AILS Segmented Alerting Equations

As discussed, the segmented alerting system / algorithm projects the intruder's future trajectory into two segments; a coordinated, constant bank angle turn segment to a specified critical heading, i.e., "circular" projection, followed by a straight path segment at the critical heading. Equations for the "circular" path segment are as follows:

1) $R = v_g^2 / g \tan(\phi)$, where R is the turn radius, v_g is the aircraft ground speed, g is the gravitational acceleration constant, and ϕ is the bank angle.
2) $\Psi_{dot} = v_g / R$, which represents the heading rate of the coordinated turn.

At each iteration of the alerting algorithm, an update of the intruder state is provided. Intruder state information consists of x_{io}, y_{io}, v_g, Ψ, and ϕ, i.e., cross-track position, longitudinal position, ground speed, heading and bank angle. Evader position is also updated (x_{eo}, y_{eo}).

Using this aircraft state information, projected trajectories are calculated for a range of critical headings. Intruder headings that endanger the evader aircraft are determined based on warning time and warning distance thresholds. Projection of the coordinated turn uses the following equations to compute the projected intruder cross-track and longitudinal track displacement:

3) $ct_1 = R * [\cos(\Psi_{int}) - \cos(\Psi_{critical})]$

$lt_1 = R * [\sin(\Psi_{critical}) - \sin(\Psi_{int})]$, where ct_1 and lt_1 represent the cross-track and longitudinal-track displacement of the intruder on the coordinated turn segment, based on the intruder heading, Ψ_{int}, and the projected critical heading, $\Psi_{critical}$.

The time for the intruder to cross the evader's flight path is equal to $t_{crossing} = t_1 + t_2$, given by

4) $t_1 = (\Psi_{critical} - \Psi_{int}) / \Psi_{dot}$,

$t_2 = (x_{eo} - x_{io} - ct_1) / (v_g * \sin(\Psi_{critical}))$.

The associated cross-track and longitudinal-track displacement of the intruder on the straight path segment is provided by

5) $ct_2 = v_g * \sin(\Psi_{critical}) * t_2$,

$lt_2 = v_g * \cos(\Psi_{critical}) * t_2$.

Having computed the crossing time and the expected cross-track and longitudinal-track displacement of the intruder, the next step is to predict the position of the evader aircraft at the crossing time, $t_{crossing}$. This allows computation of the predicted range between the evader and intruder aircraft. If the crossing time and predicted range between aircraft fall below warning time and distance warning thresholds, then an AILS alert is issued.

2.5.3 AILS TCAS-Like Alerting System (Algorithm)

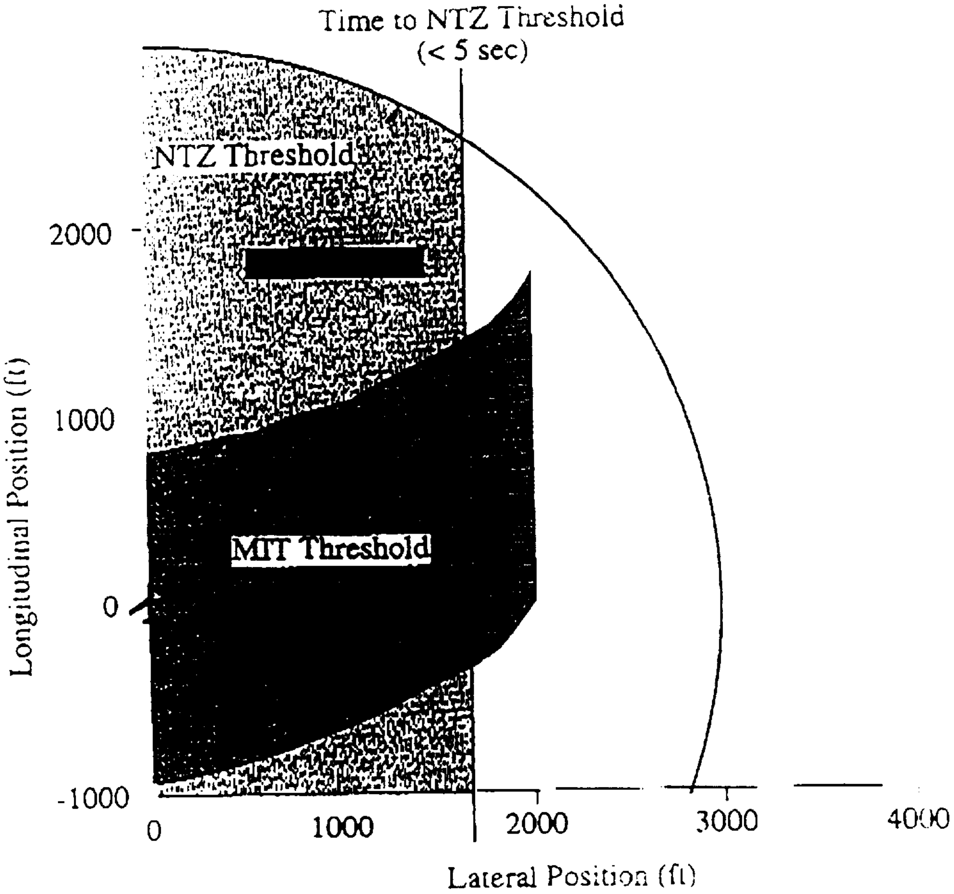
A third alerting approach that was evaluated is similar to the approach used by TCAS. Essentially, the algorithm that was evaluated computes time to closest approach based on relative range and range rate between the intruder and own aircraft. We modified the TCAS DMOD threshold to reflect a 500 ft distance.

2.5.4 AILS MIT Alerting System (Algorithm)

The MIT alerting algorithm utilizes aircraft velocity, position, heading and bank angle to determine collision risk zones. Intruder and evader aircraft states (velocity, heading and bank angles) are monitored to determine when the relative position between aircraft places the intruder within the collision risk zone. In the event the collision risk zone is entered, the cross track distance between these aircraft is examined to determine if sufficient time is still available to hold off taking evasive action, or if an evasive maneuver is required. Figure 2-15 illustrates the MIT alerting system concept. Also included in this figure is the depiction of the Non Transgression Zone (NTZ) alerting threshold used by the PRM system [3].

From Figure 2-15, the evader aircraft is shown at location (0, 0). The MIT alerting thresholds for the collision risk area are determined as a function of aircraft state information (velocity, heading, and bank angle). If the intruder falls within the collision risk area as determined by the alerting thresholds, and is within the lateral position offset, then an alert is issued.

Comparision of alerting regions used by the PRM and MIT indicates that the NTZ (PRM) may provide alerts in regions that do not necessarily warrant an alert (lighter colored region). Conversely, the MIT algorithm may actually provide a greater level of protection than the NTZ as indicated by the dark area that is outside the NTZ.



(Source: J. Kuchar, B. Carpenter - MIT)

Figure 2-15 MIT Alerting Algorithm

3. AILS Alerting Monte Carlo Simulation Approach

Previous PRM alerting simulations utilized Monte Carlo simulations to evaluate the performance of the associated PRM alerting system. In this study, Monte Carlo simulations were also utilized to evaluate the AILS alerting algorithms present in the previous section. Since our goal was to examine new aircraft state representations of the dynamic blunder environment in order to find an improved alerting system, we took the approach to obtain actual flight track state information from our Fokker 70 part-task simulator. A number of manually flown flight track templates were generated to represent various normal approaches, blunder approaches, and evasive maneuvers. Approaches were flown in foggy conditions to emulate IMC, and moderate wind gusts in all three dimensions of the coordinate system (x, y, z) to emulate turbulence. The manual approaches were flown without flight director guidance, with the pilot only flying to the course deviation dots on the CDI display.

Each approach flown was repeated at three different approach speeds; 130 knots, 145 knots, and 160 knots. This was done to allow selection of a variety of flight track pairs and aircraft dynamics for both, the evader and intruder aircraft, to allow a range of realistic approach geometries. A fast intruder following behind the evader, or a slow intruder leading the evader can each result in blunder scenarios that will lead to a collision or near miss, i.e., an incident, unless AILS alerting resolves the conflict.

The Monte Carlo simulation selects a pair of flight track templates to represent the flight track of the intruder and the evader aircraft. These templates are distributed randomly in cross track, longitudinal track, and location of blunder start. The cross-track probability distribution typically used emulates the cross-track deviations obtained from Memphis PRM test data [3]. This distribution is zero mean Gaussian, with a programmable standard deviation, σ. Two cross-track distributions were used most frequently; 1) $\sigma = 327$ ft at 10 nmi from runway threshold to represent a Type I ILS approach (navigation system error) with the pilot flying to within 1 dot deviation (flight technical error), and 2) $\sigma = 0$, relying only on the cross track errors represented in the flight track template.

Longitudinal track offsets simulated were uniformly distributed over +/- 3,000 ft. Blunder start offsets were also uniformly distributed over +/- 10,000 ft.

Independent variables for the simulation were runway spacing, number of track pair iterations to be simulated, and the alerting threshold for both time prediction, Tau, and a protection volume threshold to provide for adequate separation assurance to 500 ft closest point of approach (CPA). Most simulations used Tau = 20 seconds to represent the longest response time latency expected from the AILS alerting system. Results from NASA's flight simulator experiment using subject pilots will provide an indication of pilot response time that can be folded back into this simulation for assessing AILS alerting simulation performance.

3.1 Alerting Simulation Assumptions

A number of assumptions were made prior to performing the Monte Carlo simulations:

1) All track scenarios / encounters will be assumed to occur at co-altitude. This assumption was made to simplify the alerting study by keeping the problem within the lateral

dimension. This is viewed as a worst case approach since the altitude dimension provides an added degree of freedom, that mitigates the possibility of an incident.

2) The "turn-on" to localizer during localizer intercept is excluded from the flight track templates. The purpose is to focus the alerting problem from when aircraft are "stable" on localizer through the end of the approach path. Procedural altitude separation during localizer intercept should provide the necessary separation assurance.
3) Evasive maneuvers are "cut and paste" to the evader track once an alert is issued and the appropriate pilot / aircraft response time has transpired.
4) While flight track state variable data was recorded at an approximately 33 Hz rate, the actual data update rates used in the Monte Carlo simulation was approximately 2 Hz. This is commensurate with planned ADS-B Extended Squitter rates by Mode-S transponders.
5) Effects of measurement errors / uncertainties in aircraft state data can be applied to the state data in the flight track templates.

3.2 Flight Track Templates

A note on the Fokker 70 flight simulator which was used to generate the flight track templates used in the AILS Monte Carlo simulation. The Fokker 70 is a 100 passenger aircraft, representative of typical air transports. This part-task simulator was used to generate piloted flight tracks since it was readily available for use. The Fokker 70 part-task simulator was not equipped with rudder pedals and the pilots utilized the side-stick controller to adjust for gust induced heading changes. This may have accentuated the extent of bank angle activity. However, autopilot approaches / landings confirmed similar bank angle activity. It should also be noted that some pilots use rudder pedals to maintain heading during wind gusts, while others use the side-stick controller.

For each flight track template the following aircraft state variables were recorded: bank angle/roll, pitch angle, yaw/heading, ground speed, and barometric altitude. Initial flight tracks flown were subjected to JAR All Weather Operations (AWO) specified "limit" wind conditions in the x, y, and z directions. "Limit" winds provide conditions at the extreme end of required aircraft autoland capability. "Limit" winds induced extreme turbulence which resulted in substantial bank angle activity. It was later decided to scale back to moderate turbulence wind gusts since it is unlikely that independent parallel runway operation can be conducted in extreme wind conditions.

In flying approaches to generate flight track templates, ILS beam errors were not included and were assumed negligible. Two pilots were used to fly flight track templates; one a former airline pilot, the other a less experienced general aviation pilot with moderate experience in flying the Fokker 70 aircraft model. Pilots used the course deviation dots for guidance. The autothrottle was enabled, and yaw damper and turn coordination were also enabled.

Flight track templates flown consisted of 1) normal approach tracks, 2) a 30 degree standard rate turn (worst case) blunder, 3) a 15 degree turn blunder, 4) a 5 degree constant bank angle blunder, 5) a 10 degree heading blunder, 6) a 5 degree heading blunder, 7) a fake blunder (i.e., a turn toward the evader, followed by a return to the desired approach path), and 8) a drift off course away from the evader, with a sudden adjustment to return to own flight path with some overshoot toward the evader.

Figures 3-1 to 3-4 illustrate the flight track template state variables that were recorded for the 30 degree worst case blunder for a ground speed of 145 knots. Figure 3-1 shows the cross track and along track performance of the piloted approach. Intercept of localizer occurs on the left side of the plot. After becoming established on localizer for most of the approach path, the 30 degree blunder commences (toward the right hand side of the plot). Figure 3-2 shows both bank angle and pitch information. Note the large bank angles associated with localizer intercept and the 30 degree blunder. Figure 3-3 and 3-4 show ground track heading and barometric altitude, respectively. The remaining flight track templates for all types of approaches are documented in Appendix C.

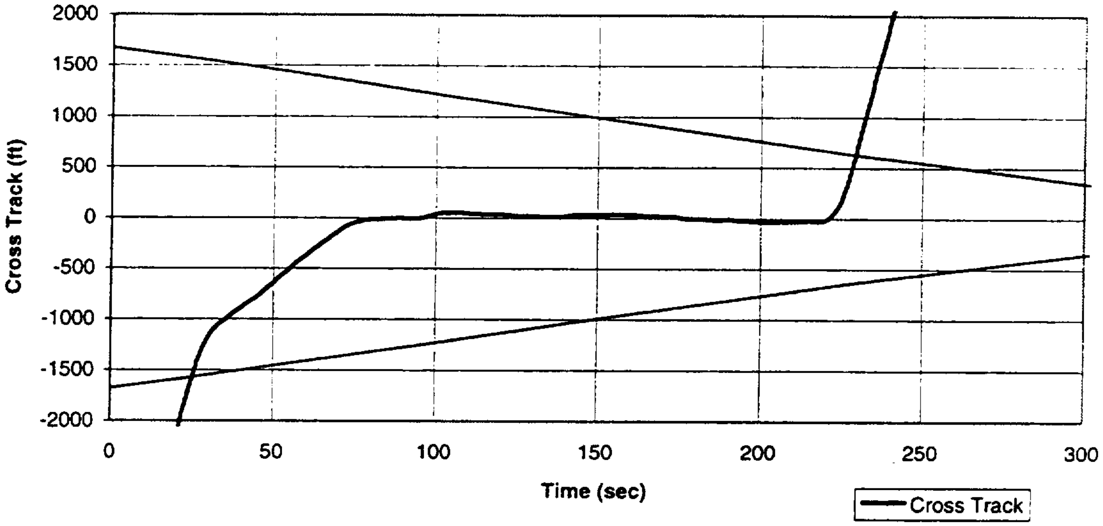


Figure 3-1 30 Degree Heading Blunder - Cross Track

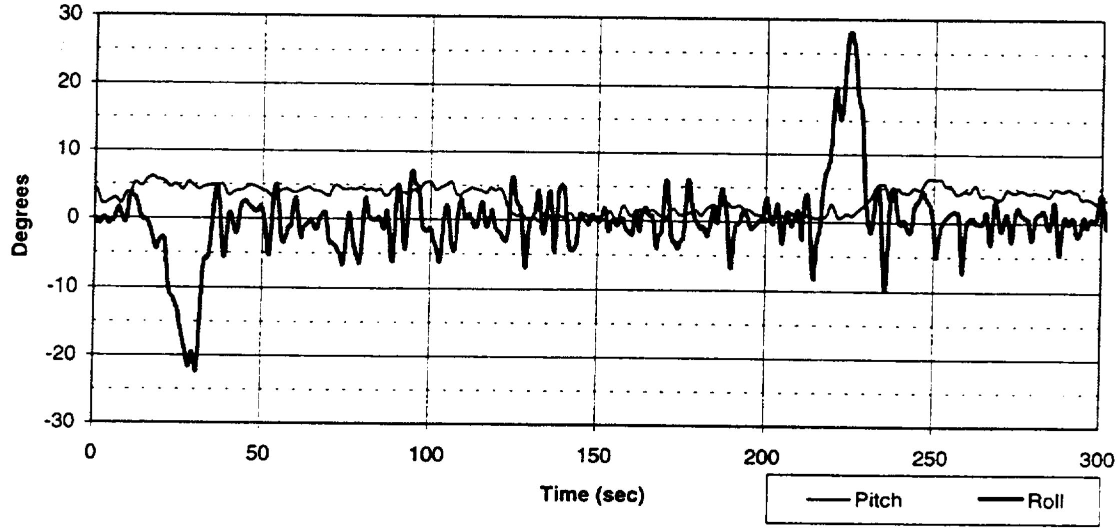


Figure 3-2 30 Degree Heading Blunder - Bank Angle/Roll and Pitch

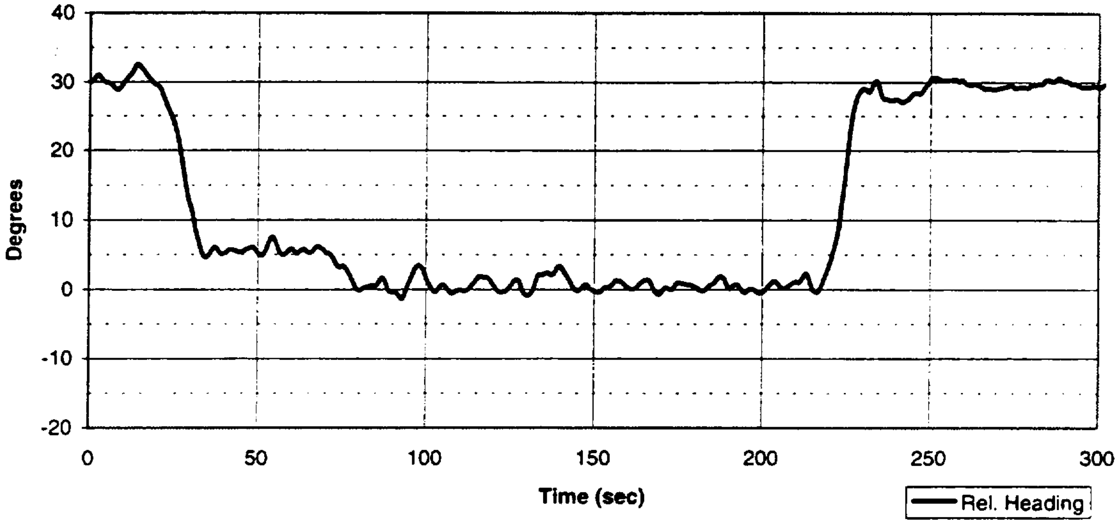


Figure 3-3 30 Degree Heading Blunder - Ground Track Heading

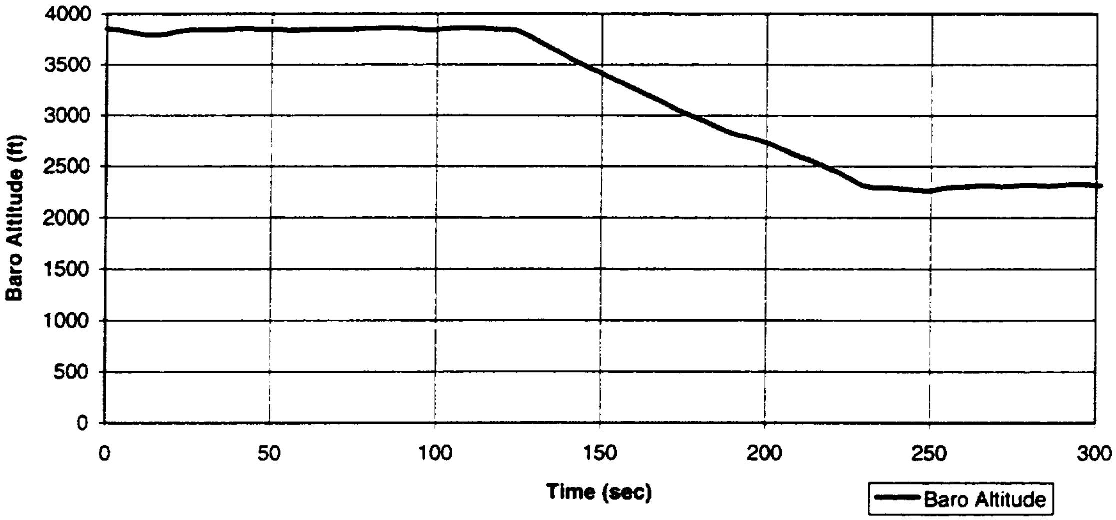


Figure 3-4 30 Degree Heading Blunder - Barometric Altitude

3.3 *Cross Track Distributions - Analysis of Total System Error (TSE)*

The Total System Error (TSE) is defined as the total error between the desired flight path and the actual flight path. TSE is comprised of navigation system and flight technical errors. The Navigation System Error (NSE) is the difference between the true aircraft position and the sensed or measured aircraft position. The Flight Technical Error (FTE) is the error associated with controlling the aircraft flight path to null the deviation (or error signal) as determined by the navigation system.

Assuming that the NSE and FTE errors are independent and normally distributed, the standard deviation of the TSE is related to the NSE and FTE as:

$$\mathrm{TSE} = (\mathrm{NSE}^2 + \mathrm{FTE}^2)^{0.5}.$$

An analysis was performed to determine the extent of TSE or cross track error for ILS and GPS-based approach navigation systems for both manual and autopilot approaches. Table 3-1 provides a summary of results. Figure 3-5 provides a graphical representation of the results in Table 3-1. Appendix B provides additional details of the analysis.

Note: A common cross-track distribution used throughout the AILS simulation program used $\sigma = 327$ ft at 10 nmi from runway threshold to represent a Type I ILS approach (navigation system error) with the pilot flying to within 1/2 dot deviation (FTE).

Navigation System & Type of Approach/Landing	**Navigation System Error (ft)**			**Flight Technical Error (ft)**			**Total System Error (ft)**		
	5 nmi	10 nmi	15 nmi	5 nmi	10 nmi	15 nmi	5 nmi	10 nmi	15 nmi
Type I ILS, Manual (1/2 dot)	299	524	749	283	495	708	411	721	1031
Type I ILS, Manual (1 dot)	299	524	749	565	990	1415	640	1120	1601
Type III ILS, Autopilot	286	502	717	100	100	100	303	511	724
Std. GPS, Manual (1/2 dot)	328	328	328	283	495	708	433	594	780
Cat I GPS, Manual (1/2 dot)	26	26	26	283	495	708	284	496	708
Cat I GPS, Autopilot	26	26	26	100	100	100	103	103	103

Table 3-1 Summary of Total System Error (TSE)

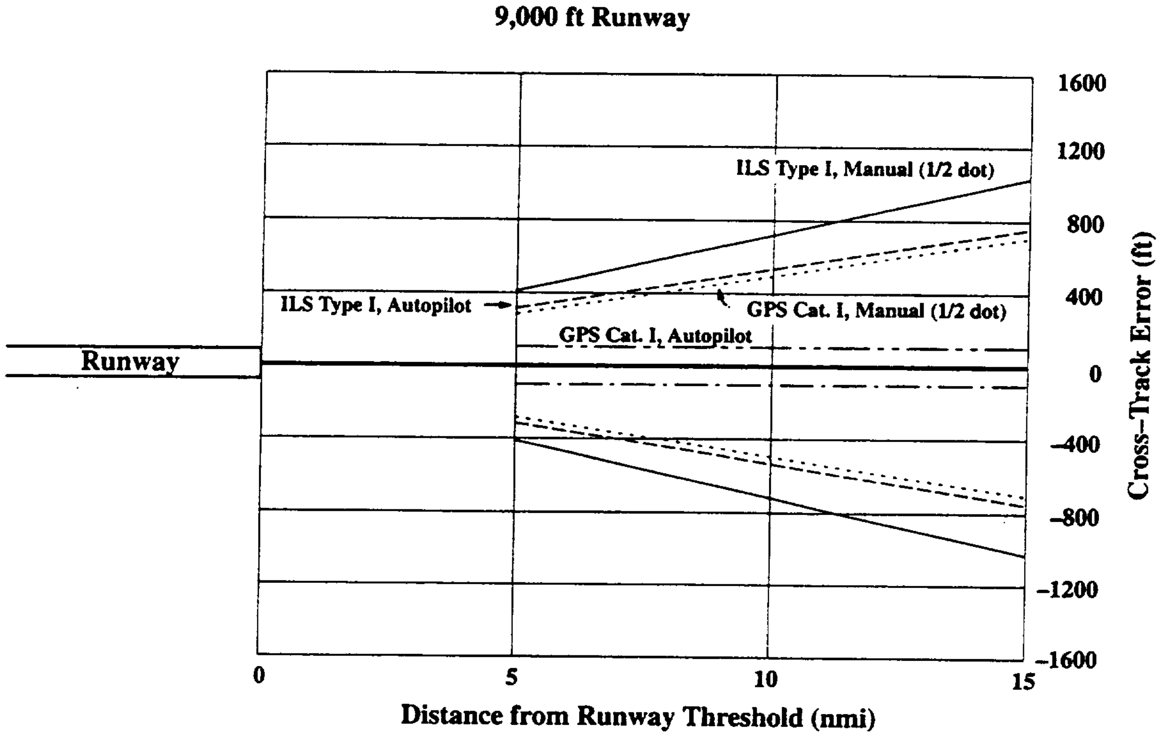


Figure 3-5 Graphical Summary of Total System Error (TSE)

3.4 Pilot Response Time Distribution

Figure 3-6 illustrates the time distribution used to simulate variations in pilot responses to an AILS alert before taking evasive action. A Rayleigh distribution with a standard deviation, σ, of 5 seconds was used. For this distribution, 99% of response times are within 15 seconds. The selected response time distribution is consistent with the PRM report [3].

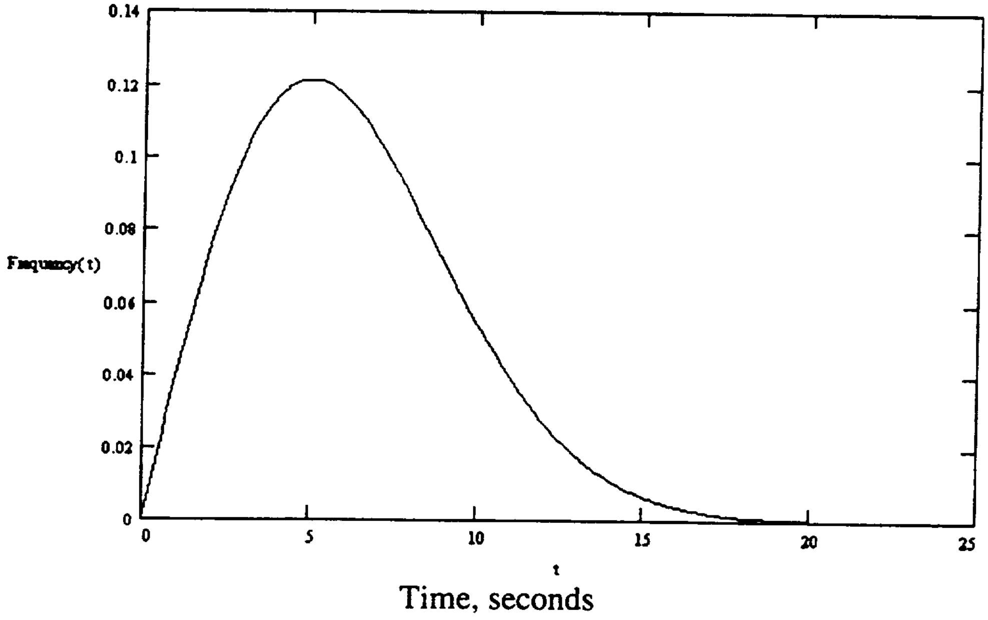


Figure 3-6 Pilot Response Time - Rayleigh Distribution (σ = 5 seconds)

3.5 AILS Alerting - Monte Carlo Simulator

A top-level block diagram of the AILS Alerting Simulator developed for this study is shown in Figure 3-7. The following paragraphs describe the simulator operation.

To start the simulation, the program reads flight track templates that were recorded for both the intruder and evader aircraft from external files. Eight flight track scenarios were flown using Collins' Fokker 70 part-task simulator. Scenarios include normal approaches and also include blunder tracks and fake blunders. These flight tracks are then flown against each other to exercise the alerting systems. Aircraft data used by the parallel approach simulator include the aircraft's position (latitude, longitude, and altitude), bank angle, air speed, and heading. Independent variables input via the command line include the runway separation, the cross track distribution, the long track distribution, the pilot/aircraft response time, and the number of Monte-Carlo runs.

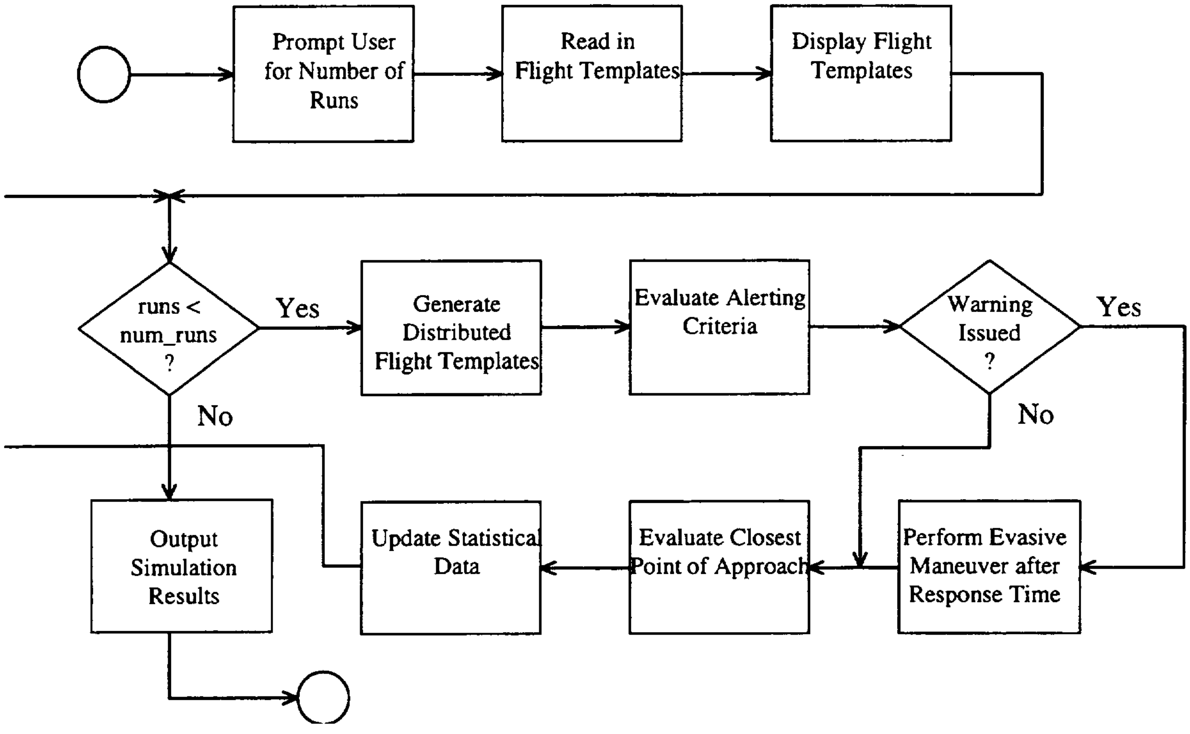


Figure 3-7 Parallel Approach Simulator - Top-Level Block Diagram

Once the template files are read, the simulator begins to simulate the parallel approaches. For each run, the flight templates are first distributed in cross track, long track, air speed, and blunder start position according to specified probability distributions. Probably distributions are discussed below. Once the templates are distributed, each aircraft is flown down its respective approach path. For each pair of flight tracks, the simulation evaluates the alerting criteria and determines the closest point of approach (CPA) between the two aircraft. If the conditions of the alerting criteria are met, a warning is issued to the aircraft. After a random period of time which simulates pilot response time, the own aircraft performs an evasive maneuver. For each pair of flight tracks, false alarms and missed detection statistics are updated.

The outputs of the simulator are the probability of missed detection, correct detection, false alarm, warning, and caution for each of the alerting systems tested. In addition, the CPA cumulative distribution function is also computed and output. In addition to these simple outputs, we have developed an integrated debugging system to allow a more detailed analysis of alerting performance.

4. Top-Level Summary of AILS Alerting Performance

This section provides a summary of alerting performance for the AILS Segmented and MIT alerting systems (algorithms). These algorithms are the best performers and represent the work of both Collins and MIT. To allow for comparison of results, MIT provided their alerting algorithm to allow Collins to evaluate it's performance using the Collins Monte Carlo alerting simulator described above.

One primary difficulty in assessing performance of AILS alerting algorithms is in determining which probability distributions should be used for cross-track and longitudinal track offsets, and pilot response time. In addition, the type of evasive maneuver also has significant impact. Some of these answers will not be obtained until human factors and flight simulator experiments are performed. NASA is currently conducting its initial flight simulator experiments on evaluating a prototype AILS system. It is expected that some of the results obtained from these experiments will provide useful inputs to these Monte Carlo AILS alerting simulations.

Until this feedback is obtained, we have assumed two different simulation scenarios; one using "ideal" probability distributions and one using "non-ideal" distributions. Table 4-1 summarizes these scenarios.

	Ideal Distributions	**Non-Ideal Distributions**
Cross-track offset	zero	Manual ILS approach, 1/2 dot flight technical error
Longitudinal-track offset	+/-9,000 ft range	+/- 3,000 ft range
Pilot response time	fixed at 5 seconds	Rayleigh distributed, σ = 5 sec, 99% within 15 seconds
Avionics sensor data uncertainties	None	Yes
Data update rate	2 Hz	1 Hz
Data link failure rate	None	10%
Evasive maneuver	2,000 ft/min climb at 0.25 g, 40° heading turn, 30° bank angle, 10°/sec bank rate	2,000 ft/min climb at 0.25 g, 40° heading turn with adaptive heading, 30° bank angle, 5° /sec bank rate

Table 4-1 Summary of Ideal and Non-Ideal Distributions used in AILS Alerting Evaluations

Tables 4-2 through 4-5 summarize AILS alerting performance for the AILS Segmented and MIT alerting algorithms for both ideal and non-ideal distributions. For each flight track scenario, i.e., pair of intruder and evader flight track templates, 5000 distributed track pairs were simulated. Thus, for all blunder types, 35000 runs are represented in each table. Flight track templates for all scenarios simulated are provided in Appendix C.

Some explanation of the parameters in the tables is in order. "Normal run false alarms" refers to the percentage of runs that had a false alarm when both aircraft fly a normal approach. Normal run false alarms are highly undesirable since they erode the capacity improvements gained by making parallel approaches to closely spaced runways. Our goal of zero false alarms was easily achieved for ideal distributions (Tables 4-2 and 4-3) and nearly met for non-ideal distributions (Tables 4-4 and 4-5). "Total false alarms" is the percentage of all runs that had a false alarm. The fake blunder scenarios provide the greatest number of false alarms. False alarms for these scenarios are difficult to avoid because the fakes are quite threatening and the alerting systems have difficulty in discriminating between fake and actual blunders (particularly at such close runway spacings). Again, our goal of less than 5% was easily achieved for ideal distributions and nearly met with non-ideal distributions. "False alarms with near miss" gives an indication of the accuracy of the alerting system. It is the percentage of false alarm that actually come within 1,000 feet of own aircraft (without an evasive maneuver). Therefore, although an incident would not have occurred, the situation may be interpreted as threatening. Good alerting accuracy results in a large percentage of "near miss false alarms". Due to the effect of the fake blunders, this parameter was further divided into two categories, "total" and "blunders". Blunder scenarios are those that actually cross the evader's runway. We meet the greater than 95% goal for each runway spacing except at 3,400 feet. The lower accuracy at larger runway spacings is reasonable since there is more potential variation in the intruder's flight path for the longer flight distance. "Premature false alarms" are warnings that occur before the blunder event commences. These are similar in nature to the normal run false alarms and are considered highly undesirable. No premature false alarms occurred for ideal distributions. Non-ideal distributions exhibited a 2.6% premature false alarm rate for 1,700 ft runway spacings.

The "number of potential incidents" refers to the number of incidents (< 500 foot CPA) that would occur if own aircraft does not perform an evasive maneuver. A large number of potential incidents are desired to fully test the alerting systems. "Number of unresolved incidents" refers to the number of incidents that occur even though own aircraft performs an evasive maneuver. For ideal distributions, MIT alerting resolved all incidents while segmented alerting resolved all but one incident.

"Incident resolution" is the percentage of potential incidents that are resolved successfully by an evasive maneuver. Clearly, we want this value to be as high as possible. For the ideal distributions, segmented alerting achieved better than 99.9% incident resolution. The final entry in the tables is the percentage of incidents in which no warning was issued, (i.e., Missed Detections without alarms). Anything other than zero percent for this parameter indicates problems with alerting thresholds that must be eliminated.

While the initial sub-table summarizes alerting performance for all flight track scenarios, the remaining sub-tables within each table provide alerting results for each individual flight track scenario (blunder, normal, or fake blunder).

Table 4-2 Segmented Alerting
Ideal

Segmented Alerting (rev 8.1)

Long Track Range = 18228 ft
Cross Track Std Dev = 0 ft
Number of Runs = 5000 x 7 scenarios
Alert Time = 20 sec
Warning Threshold = 600 ft
Pilot/Aircraft Response Time = Rayleigh ($\sigma = 5$ s)
Winds = 12.5 knots
Evasive Maneuver: $30^\circ\ \theta$ to $30^\circ\ \Psi$ w/ 0.25 g pull-up to 2000 ft/min climb
Heading Uncertainty = 0 °
Bank Uncertainty = 0 °
Vg Uncertainty = 0 knots
Update Rate = 2 Hz
Position Uncertainty = 0 feet
Link Failure Rate = 0 %

Table 1. Alerting goals and achievements for selected runway spacings (all blunders)

Parameters	Goal	1700 ft	2000 ft	2500 ft	3400 ft
Normal Run FA's	0%	0.00%	0.00%	0.00%	0.00%
Total # FA's	< 5 %	3.0%	2.9%	2.7%	1.4%
FA's with Near Miss (< 1000 ft)					
Total	> 50 %	76.8%	58.1%	56.7%	78.5%
Blunders	> 95 %	98.8%	98.3%	95.0%	81.8%
Premature FA's	0%	0.0%	0.0%	0.0%	0.0%
Number of Potential Incidents	NA	1292	1234	1097	970
Number of Unresolved Incidents	NA	0	1	1	1
Incident Resolution	> 98 %	100.0%	99.9%	99.9%	99.9%
MD's without Alarm	0%	0.0%	0.0%	0.0%	0.0%
MD's due to Incorrect Res. Time	< 2 %	13.8%	4.5%	1.2%	2.6%

Table A1. Segmented performance for 30° heading blunder.

Parameters	Goal	1700 ft	2000 ft	2500 ft	3400 ft
Total # FA's	< 5 %	2.0%	2.5%	2.1%	2.1%
FA's with Near Miss (< 1000 ft)	> 95 %	100.0%	100.0%	100.0%	100.0%
Premature FA's	0%	0.0%	0.0%	0.0%	0.0%
Number of Potential Incidents	NA	296	284	298	308
Number of Unresolved Incidents	NA	0	0	0	0
Incident Resolution	> 98 %	100.0%	100.0%	100.0%	100.0%
Average Response Time (Detect to Incident)	> 20 sec	0.0	0.0	0.0	0.0
MD's without Alarm	0%	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!
MD's due to Incorrect Res. Time	< 2 %	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!

Table A2. Segmented performance for 15° heading blunder.

Parameters	Goal	1700 ft	2000 ft	2500 ft	3400 ft
Total # FA's	< 5 %	2.7%	3.0%	2.6%	2.0%
FA's with Near Miss (< 1000 ft)	> 95 %	100.0%	99.3%	94.8%	82.4%
Premature FA's	0%	0.0%	0.0%	0.0%	0.0%
Number of Potential Incidents	NA	280	278	267	242
Number of Unresolved Incidents	NA	0	1	1	1
Incident Resolution	> 98 %	100.0%	99.6%	99.6%	99.6%
Average Response Time (Detect to Incident)	> 20 sec	0.0	6.8	6.2	0.6
MD's without Alarm	0%	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!

Table 4-2 Segmented Alerting (continued)
Ideal

MD's due to Incorrect Res. Time	< 2 %	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!

Table A3. Segmented performance for 5° bank angle blunder.

Parameters	Goal	1700 ft	2000 ft	2500 ft	3400 ft
Total # FA's	< 5 %	1.3%	1.4%	1.6%	1.6%
FA's with Near Miss (< 1000 ft)	> 95 %	100.0%	100.0%	100.0%	100.0%
Premature FA's	0%	0.0%	0.0%	0.0%	0.0%
Number of Potential Incidents	NA	292	294	299	300
Number of Unresolved Incidents	NA	0	0	0	0
Incident Resolution	> 98 %	100.0%	100.0%	100.0%	100.0%
Average Response Time (Detect to Incident)	> 20 sec	0.0	0.0	0.0	0.0
MD's without Alarm	0%	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!
MD's due to Incorrect Res. Time	< 2 %	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!

Table A4. Segmented performance for 10° heading blunder.

Parameters	Goal	1700 ft	2000 ft	2500 ft	3400 ft
Total # FA's	< 5 %	2.1%	2.1%	2.1%	1.9%
FA's with Near Miss (< 1000 ft)	> 95 %	95.5%	94.5%	85.1%	60.0%
Premature FA's	0%	0.0%	0.0%	0.0%	0.0%
Number of Potential Incidents	NA	271	261	231	120
Number of Unresolved Incidents	NA	0	0	0	0
Incident Resolution	> 98 %	100.0%	100.0%	100.0%	100.0%
Average Response Time (Detect to Incident)	> 20 sec	0.0	0.0	0.0	0.0
MD's without Alarm	0%	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!
MD's due to Incorrect Res. Time	< 2 %	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!

Table A5. Segmented performance for 5° heading blunder.

Parameters	Goal	1700 ft	2000 ft	2500 ft	3400 ft
Total # FA's	< 5 %	3.6%	2.7%	2.4%	0.0%
FA's with Near Miss (< 1000 ft)	> 95 %	98.9%	97.9%	97.6%	#DIV/0!
Premature FA's	0%	0.0%	0.0%	0.0%	#DIV/0!
Number of Potential Incidents	NA	153	117	2	0
Number of Unresolved Incidents	NA	0	0	0	0
Incident Resolution	> 98 %	100.0%	100.0%	100.0%	#DIV/0!
Average Response Time (Detect to Incident)	> 20 sec	0.0	0.0	0.0	0.0
MD's without Alarm	0%	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!
MD's due to Incorrect Res. Time	< 2 %	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!

Table A6. Segmented performance for fake blunder.

Parameters	Goal	1700 ft	2000 ft	2500 ft	3400 ft
Total # FA's	< 5 %	4.2%	0.0%	0.0%	0.0%
FA's with Near Miss (< 1000 ft)	> 95 %	47.2%	0.0%	0.0%	0.0%

Table 4-3 MIT Alerting - Ideal

MIT Alerting (rev 13_1)

Long Track Range = 18228 ft
Cross Track Std Dev = 0 ft
Number of Runs = 5000 x 7 scenarios
Alert Time = NA
Warning Threshold = NA
Pilot/Aircraft Response Time = Fixed 5 sec
Winds = 12.5 knots
Evasive Maneuver: 30° θ max bank
Heading Uncertainty = 0 °
10deg/sec bank rate, 30° Ψ
Bank Uncertainty = 0 °
2,000 ft/min climb, 0.25 g
Vg Uncertainty = 0 knots
Update Rate = 2 Hz
Position Uncertainty = 0 feet
Link Failure Rate = 0 %

Table 1. Alerting goals and achievements for selected runway spacings (all blunders)

Parameters	Goal	1700 ft	2000 ft	2500 ft	3400 ft
Normal Run FA's	0%	0.00%	0.00%	0.00%	0.00%
Total # FA's	< 5 %	4.7%	4.9%	4.4%	2.7%
FA's with Near Miss (< 1000 ft)					
Total	> 50 %	80.3%	63.9%	65.6%	83.1%
Blunders	> 95 %	97.1%	93.8%	90.0%	83.1%
Premature FA's	0%	0.0%	0.0%	0.0%	0.0%
Number of Potential Incidents	NA	1292	1234	1097	970
Number of Unresolved Incidents	NA	0	0	0	0
Incident Resolution	> 98 %	100.0%	100.0%	100.0%	100.0%
MD's without Alarm	0%	0.0%	0.0%	0.0%	0.0%

Table 2. Alerting goals and achievements for selected runway spacings (b30)

Parameters	Goal	1700 ft	2000 ft	2500 ft	3400 ft
Total # FA's	< 5 %	4.5%	5.1%	5.6%	4.7%
FA's with Near Miss (< 1000 ft)	> 95 %	96.5%	89.5%	83.2%	100.0%
Premature FA's	0%	0.0%	0.0%	0.0%	0.0%
Number of Potential Incidents	NA	296	284	298	308
Number of Unresolved Incidents	NA	0	0	0	0
Incident Resolution	> 98 %	100.0%	100.0%	100.0%	100.0%
Average Response Time (Detect to Incident)	> 20 sec	0.0	0.0	0.0	0.0
MD's without Alarm	0%	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!

Table 3. Alerting goals and achievements for selected runway spacings (b15)

Parameters	Goal	1700 ft	2000 ft	2500 ft	3400 ft
Total # FA's	< 5 %	5.0%	5.2%	4.4%	4.1%
FA's with Near Miss (< 1000 ft)	> 95 %	94.3%	92.5%	94.9%	85.7%
Premature FA's	0%	0.0%	0.0%	0.0%	0.0%
Number of Potential Incidents	NA	280	278	267	242
Number of Unresolved Incidents	NA	0	0	0	0
Incident Resolution	> 98 %	100.0%	100.0%	100.0%	100.0%
Average Response Time (Detect to Incident)	> 20 sec	0.0	0.0	0.0	0.0
MD's without Alarm	0%	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!

Table 4-3 MIT Alerting - Ideal (continued)

Table 4. Alerting goals and achievements for selected runway spacings (sl5)

Parameters	Goal	1700 ft	2000 ft	2500 ft	3400 ft
Total # FA's	< 5 %	3.6%	3.6%	4.0%	3.9%
FA's with Near Miss (< 1000 ft)	> 95 %	100.0%	100.0%	100.0%	100.0%
Premature FA's	0%	0.0%	0.0%	0.0%	0.0%
Number of Potential Incidents	NA	292	294	299	300
Number of Unresolved Incidents	NA	0	0	0	0
Incident Resolution	> 98 %	100.0%	100.0%	100.0%	100.0%
Average Response Time (Detect to Incident)	> 20 sec	0.0	0.0	0.0	0.0
MD's without Alarm	0%	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!

Table 5. Alerting goals and achievements for selected runway spacings (slo)

Parameters	Goal	1700 ft	2000 ft	2500 ft	3400 ft
Total # FA's	< 5 %	4.4%	4.1%	4.1%	3.1%
FA's with Near Miss (< 1000 ft)	> 95 %	95.7%	91.2%	83.2%	55.3%
Premature FA's	0%	0.0%	0.0%	0.0%	0.0%
Number of Potential Incidents	NA	271	261	231	120
Number of Unresolved Incidents	NA	0	0	0	0
Incident Resolution	> 98 %	100.0%	100.0%	100.0%	100.0%
Average Response Time (Detect to Incident)	> 20 sec	0.0	0.0	0.0	0.0
MD's without Alarm	0%	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!

Table 6. Alerting goals and achievements for selected runway spacings (sh5)

Parameters	Goal	1700 ft	2000 ft	2500 ft	3400 ft
Total # FA's	< 5 %	4.8%	3.7%	2.2%	0.0%
FA's with Near Miss (< 1000 ft)	> 95 %	100.0%	99.5%	96.5%	#DIV/0!
Premature FA's	0%	0.0%	0.0%	0.0%	#DIV/0!
Number of Potential Incidents	NA	153	117	2	0
Number of Unresolved Incidents	NA	0	0	0	0
Incident Resolution	> 98 %	100.0%	100.0%	100.0%	#DIV/0!
Average Response Time (Detect to Incident)	> 20 sec	0.0	0.0	0.0	0.0
MD's without Alarm	0%	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!

Table 7. Alerting goals and achievements for selected runway spacings (fake)

Parameters	Goal	1700 ft	2000 ft	2500 ft	3400 ft
Total # FA's	< 5 %	4.3%	0.0%	0.0%	0.0%
FA's with Near Miss (< 1000 ft)	> 95 %	42.4%	0.0%	0.0%	#DIV/0!
Premature FA's	0%	0.0%	0.0%	0.0%	#DIV/0!
Number of Potential Incidents	NA	0	0	0	0
Number of Unresolved Incidents	NA	0	0	0	0
Incident Resolution	> 98 %	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!
MD's without Alarm	0%	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!

Table 4-4 Segmented Alerting
- Non Ideal

Segmented Alerting (rev 12)

Long Track Range = 6000 ft
Number of Runs = 5000 x 7 scenarios
Warning Threshold = 600 ft
Winds = 12.5 knots
Heading Uncertainty = 1 °
Bank Uncertainty = 0.1 °
Vg Uncertainty = 2 knots
Position Uncertainty = 30 feet

Cross Track Std Dev = 327 ft
Alert Time = 20 sec
Pilot/Aircraft Response Time = Rayleigh (σ = 5 s)
Evasive Maneuver: 30° θ max bank
40° Ψ or > intruder Ψ
2,000 ft/min climb, 0.25g
Update Rate = 1 Hz
Link Failure Rate = 10 %

Table 1. Alerting goals and achievements for selected runway spacings (all blunders)

Parameters	Goal	1700 ft	2000 ft	2500 ft	3400 ft
Normal Run FA's	0%	0.20%	0.04%	0.00%	0.00%
Total # FA's	< 5 %	7.9%	7.8%	7.5%	4.3%
FA's with Near Miss (< 1000 ft)					
Total	> 50 %	77.7%	65.0%	58.4%	78.8%
Blunders	> 95 %	94.7%	96.9%	94.4%	85.3%
Premature FA's	0%	2.6%	0.1%	0.0%	0.0%
Number of Potential Incidents	NA	4067	3791	3411	2887
Number of Unresolved Incidents	NA	172	115	88	75
Incident Resolution	> 98 %	95.8%	97.0%	97.4%	97.4%
MD's without Alarm	0%	0.0%	0.0%	0.0%	0.0%

Table 2. Alerting goals and achievements for selected runway spacings (b30)

Parameters	Goal	1700 ft	2000 ft	2500 ft	3400 ft
Total # FA's	< 5 %	5.8%	5.9%	5.8%	5.9%
FA's with Near Miss (< 1000 ft)	> 95 %	94.1%	99.7%	100.0%	100.0%
Premature FA's	0%	5.9%	0.3%	0.0%	0.0%
Number of Potential Incidents	NA	916	905	909	878
Number of Unresolved Incidents	NA	144	82	27	11
Incident Resolution	> 98 %	84.3%	90.9%	97.0%	98.7%
Average Response Time (Detect to Incident)	> 20 sec	13.7	15.4	16.5	19.1
MD's without Alarm	0%	0.0%	0.0%	0.0%	0.0%

Table 3. Alerting goals and achievements for selected runway spacings (b15)

Parameters	Goal	1700 ft	2000 ft	2500 ft	3400 ft
Total # FA's	< 5 %	7.7%	7.9%	7.7%	6.6%
FA's with Near Miss (< 1000 ft)	> 95 %	97.2%	99.5%	93.3%	86.1%
Premature FA's	0%	2.6%	0.0%	0.0%	0.0%
Number of Potential Incidents	NA	897	881	854	736
Number of Unresolved Incidents	NA	3	4	26	33
Incident Resolution	> 98 %	99.7%	99.5%	97.0%	95.5%
Average Response Time (Detect to Incident)	> 20 sec	7.4	15.6	15.0	18.9
MD's without Alarm	0%	0.0%	0.0%	0.0%	0.0%

Table 4-4 Segmented Alerting (continued)
- Non Ideal

Table 4. Alerting goals and achievements for selected runway spacings (sl5)

Parameters	Goal	1700 ft	2000 ft	2500 ft	3400 ft
Total # FA's	< 5 %	4.7%	4.6%	5.0%	4.5%
FA's with Near Miss (< 1000 ft)	> 95 %	92.4%	99.1%	100.0%	100.0%
Premature FA's	0%	7.6%	0.9%	0.0%	0.0%
Number of Potential Incidents	NA	912	897	904	918
Number of Unresolved Incidents	NA	10	19	26	19
Incident Resolution	> 98 %	98.9%	97.9%	97.1%	97.9%
Average Response Time (Detect to Incident)	> 20 sec	17.5	16.6	16.0	18.5
MD's without Alarm	0%	0.0%	0.0%	0.0%	0.0%

Table 5. Alerting goals and achievements for selected runway spacings (slo)

Parameters	Goal	1700 ft	2000 ft	2500 ft	3400 ft
Total # FA's	< 5 %	6.3%	6.2%	6.6%	6.4%
FA's with Near Miss (< 1000 ft)	> 95 %	93.3%	89.5%	88.5%	68.4%
Premature FA's	0%	2.8%	0.0%	0.0%	0.0%
Number of Potential Incidents	NA	850	799	712	355
Number of Unresolved Incidents	NA	4	4	9	12
Incident Resolution	> 98 %	99.5%	99.5%	98.7%	96.6%
Average Response Time (Detect to Incident)	> 20 sec	7.5	11.2	17.6	14.5
MD's without Alarm	0%	0.0%	0.0%	0.0%	0.0%

Table 6. Alerting goals and achievements for selected runway spacings (sh5)

Parameters	Goal	1700 ft	2000 ft	2500 ft	3400 ft
Total # FA's	< 5 %	9.9%	8.7%	5.4%	0.0%
FA's with Near Miss (< 1000 ft)	> 95 %	95.6%	97.3%	93.4%	#DIV/0!
Premature FA's	0%	3.0%	0.0%	0.0%	#DIV/0!
Number of Potential Incidents	NA	480	309	32	0
Number of Unresolved Incidents	NA	11	6	0	0
Incident Resolution	> 98 %	97.7%	98.1%	100.0%	#DIV/0!
Average Response Time (Detect to Incident)	> 20 sec	7.7	12.7	0.0	0.0
MD's without Alarm	0%	0.0%	0.0%	#DIV/0!	#DIV/0!

Table 7. Alerting goals and achievements for selected runway spacings (fake)

Parameters	Goal	1700 ft	2000 ft	2500 ft	3400 ft
Total # FA's	< 5 %	9.6%	2.1%	0.0%	0.0%
FA's with Near Miss (< 1000 ft)	> 95 %	47.8%	10.4%	0.0%	0.0%
Premature FA's	0%	0.2%	0.0%	0.0%	0.0%
Number of Potential Incidents	NA	12	0	0	0
Number of Unresolved Incidents	NA	1	0	0	0
Incident Resolution	> 98 %	91.7%	#DIV/0!	#DIV/0!	#DIV/0!
MD's without Alarm	0%	0.0%	#DIV/0!	#DIV/0!	#DIV/0!

Table 4-5 MIT Alerting
Non-Ideal

MIT Alerting (rev 12)

Long Track Range = 6000 ft
Number of Runs = 5000 x 7 scenarios
Warning Threshold = 600 ft
Winds = 12.5 knots
Heading Uncertainty = 1 °
Bank Uncertainty = 0.1 °
Vg Uncertainty = 2 knots
Position Uncertainty = 30 feet

Cross Track Std Dev = 327 ft
Alert Time = 20 sec
Pilot/Aircraft Response Time = Rayleigh ($\sigma = 5$ s)
Evasive Maneuver: 30° θ max bank
40° Ψ or > intruder Ψ
2,000 ft/min, 0.25 g
Update Rate = 1 Hz
Link Failure Rate = 10 %

Table 1. Alerting goals and achievements for selected runway spacings (all blunders)

Parameters	Goal	1700 ft	2000 ft	2500 ft	3400 ft
Normal Run FA's	0%	0.16%	0.00%	0.00%	0.00%
Total # FA's	< 5 %	12.6%	12.6%	11.8%	7.9%
FA's with Near Miss (< 1000 ft)					
Total	> 50 %	83.9%	75.0%	67.5%	83.3%
Blunders	> 95 %	95.9%	94.4%	89.1%	83.5%
Premature FA's	0%	0.9%	0.1%	0.0%	0.0%
Number of Potential Incidents	NA	4067	3791	3411	2887
Number of Unresolved Incidents	NA	195	125	92	115
Incident Resolution	> 98 %	95.2%	96.7%	97.3%	96.0%
MD's without Alarm	0%	0.0%	0.0%	0.0%	0.0%

Table 2. Alerting goals and achievements for selected runway spacings (b30)

Parameters	Goal	1700 ft	2000 ft	2500 ft	3400 ft
Total # FA's	< 5 %	13.1%	14.0%	14.1%	13.0%
FA's with Near Miss (< 1000 ft)	> 95 %	94.4%	91.4%	83.0%	96.7%
Premature FA's	0%	1.2%	0.3%	0.0%	0.0%
Number of Potential Incidents	NA	916	905	909	878
Number of Unresolved Incidents	NA	163	95	52	46
Incident Resolution	> 98 %	82.2%	89.5%	94.3%	94.8%
Average Response Time (Detect to Incident)	> 20 sec	13.8	15.4	16.5	17.6
MD's without Alarm	0%	0.0%	0.0%	0.0%	0.0%

Table 3. Alerting goals and achievements for selected runway spacings (b15)

Parameters	Goal	1700 ft	2000 ft	2500 ft	3400 ft
Total # FA's	< 5 %	14.0%	14.4%	12.7%	12.5%
FA's with Near Miss (< 1000 ft)	> 95 %	96.5%	96.4%	92.6%	85.3%
Premature FA's	0%	0.7%	0.1%	0.0%	0.0%
Number of Potential Incidents	NA	897	881	854	736
Number of Unresolved Incidents	NA	6	2	9	10
Incident Resolution	> 98 %	99.3%	99.8%	98.9%	98.6%
Average Response Time (Detect to Incident)	> 20 sec	18.0	11.8	22.4	22.7
MD's without Alarm	0%	0.0%	0.0%	0.0%	0.0%

Table 4-5 MIT Alerting (continued)
Non-Ideal

Table 4. Alerting goals and achievements for selected runway spacings (sl5)

Parameters	Goal	1700 ft	2000 ft	2500 ft	3400 ft
Total # FA's	< 5 %	11.5%	11.6%	11.3%	10.7%
FA's with Near Miss (< 1000 ft)	> 95 %	98.8%	100.0%	100.0%	100.0%
Premature FA's	0%	1.2%	0.0%	0.0%	0.0%
Number of Potential Incidents	NA	912	897	904	918
Number of Unresolved Incidents	NA	13	15	30	57
Incident Resolution	> 98 %	98.6%	98.3%	96.7%	93.8%
Average Response Time (Detect to Incident)	> 20 sec	16.8	16.4	16.7	16.7
MD's without Alarm	0%	0.0%	0.0%	0.0%	0.0%

Table 5. Alerting goals and achievements for selected runway spacings (slo)

Parameters	Goal	1700 ft	2000 ft	2500 ft	3400 ft
Total # FA's	< 5 %	13.1%	13.1%	12.2%	9.7%
FA's with Near Miss (< 1000 ft)	> 95 %	93.5%	88.9%	83.4%	59.9%
Premature FA's	0%	1.2%	0.1%	0.0%	0.0%
Number of Potential Incidents	NA	850	799	712	355
Number of Unresolved Incidents	NA	1	0	1	2
Incident Resolution	> 98 %	99.9%	100.0%	99.9%	99.4%
Average Response Time (Detect to Incident)	> 20 sec	0.0	0.0	12.5	3.7
MD's without Alarm	0%	0.0%	#DIV/0!	0.0%	0.0%

Table 6. Alerting goals and achievements for selected runway spacings (sh5)

Parameters	Goal	1700 ft	2000 ft	2500 ft	3400 ft
Total # FA's	< 5 %	14.2%	11.5%	5.3%	0.0%
FA's with Near Miss (< 1000 ft)	> 95 %	97.1%	97.3%	92.3%	#DIV/0!
Premature FA's	0%	0.8%	0.0%	0.0%	#DIV/0!
Number of Potential Incidents	NA	480	309	32	0
Number of Unresolved Incidents	NA	12	13	0	0
Incident Resolution	> 98 %	97.5%	95.8%	100.0%	#DIV/0!
Average Response Time (Detect to Incident)	> 20 sec	9.7	11.7	0.0	0.0
MD's without Alarm	0%	0.0%	0.0%	#DIV/0!	#DIV/0!

Table 7. Alerting goals and achievements for selected runway spacings (fake)

Parameters	Goal	1700 ft	2000 ft	2500 ft	3400 ft
Total # FA's	< 5 %	8.6%	1.7%	0.0%	0.0%
FA's with Near Miss (< 1000 ft)	> 95 %	42.8%	8.5%	0.0%	0.0%
Premature FA's	0%	0.4%	0.0%	0.0%	0.0%
Number of Potential Incidents	NA	12	0	0	0
Number of Unresolved Incidents	NA	1	0	0	0
Incident Resolution	> 98 %	91.7%	#DIV/0!	#DIV/0!	#DIV/0!
MD's without Alarm	0%	0.0%	#DIV/0!	#DIV/0!	#DIV/0!

From the results displayed in Tables 4-2 and 4-3, the segmented and MIT alerting system perform exceptionally well under ideal conditions down to 1,700 ft runway spacings for all blunder types.

For non-ideal distributions alerting performance results are less optimistic. Due to the reduced longitudinal offsets, a higher concentration of potential incidents occur. Again, each flight track scenario was run 5,000 times with these distributions for a total of 35,000 runs.

From Tables 4-4 and 4-5 it is evident that alerting performance has decreased appreciably. The number of "normal run" and "premature" false alarms at the 1,700 and 2,000 foot runway spacings is non-zero. The increase is a direct result of the reduced aircraft separation due to cross-track offset. Likewise, the number of total false alarms has also increased to ~8% for the segmented algorithm and ~12% for the MIT algorithm for all runs. As before, the number of false alarms are adversely affected by the fake blunders contributions. The percentage of near miss false alarms is still high indicating good prediction accuracy.

Incident resolution is the critical parameter here. Note that the number of potential incidents is significantly increased due to the reduced long track stagger between aircraft, so the alerting system is being tested to a greater extent. The percentage of incidents resolved is decreased to less than 95%. The decrease is due to the long response times that may be required for own aircraft to start an evasive maneuver. With at most 20 seconds prediction time prior to when an incident is likely to occur, response times on the order of 15 seconds may not give own aircraft enough time to evade the intruder. Advanced caution alerts may be one way to reduce the response time further. More investigation is needed in this area.

Incident resolution at runway spacings less than 2,500 feet are unacceptable, especially for the 30° heading blunder. At these spacings, the evader aircraft simply does not have enough advance warning to evade the intruder aircraft successfully. Again, this result is driven by the response time of own aircraft.

The next section takes a more detailed look at AILS alerting performance results provided by the simulation.

5. AILS Alerting Performance Sensitivities

This section takes a closer look at AILS alerting performance and examines sensitivities of candidate alerting algorithms to various input parameters and probability distributions.

5.1 *Performance of "TCAS-like" Alerting Algorithm*

As indicated previously, "TCAS-like" alerting simulated for AILS is similar to the approach used by TCAS. The time to closest approach, Tau, is computed to a range threshold, DMOD. For AILS DMOD is set to 500 ft. Tau is computed based on the current range and relative range rate between the intruder and evader aircraft, and DMOD. Tau is then compared to a time threshold that is based on the prediction time. As seen in Table 5-1, this algorithm has significant false alarm problems and is not useful for AILS alerting. The high-rate of false alarms is the result of close spacings between aircraft and the variability of the range rate computation in moderately turbulent conditions. At these close proximities, any appreciable closing range rate is likely to trigger an alert. For Table 5-1 $t_{predict} = 20$ sec was used for the time threshold.

Note: Parameters used for the simulation results are provided with Figures and Tables. The following conventions are followed: CT and LT refer to cross track and longitudinal track distributions, respectively; P/A refers to pilot / aircraft response time; state data update rate is denoted, typically as ~2 Hz; references to data uncertainty and data link failure rate indicate whether uncertainties due to sensor errors and data link communication failures are simulated. Refer to Table 4-1 for a list of the various ideal and non-ideal distributions used in simulations.

	1700 ft	**2000 ft**	**2500 ft**	**3400 ft**
False Alarm Rate	38.0%	40.7%	43.1%	43.5%

Table 5-1 "TCAS-Like" Alerting Performance for 30° Heading Blunder
(CT: σ=327 ft; LT: +/-3,000 ft; P/A: σ=5 sec Rayleigh;
~2 Hz; no data uncertainty; no link failures)

5.2 *Comparison of Circular, Segmented, and MIT Alerting Systems*

Alerting performance consists of two primary criteria; 1) incident resolution rate, and 2) false alarm rate. Figures 5-1 and 5-2 compare the alerting performance of Circular, Segmented, and MIT alerting systems obtained from Monte Carlo simulation using the flight track data of Appendix C.

From Figure 5-1 it is evident that there is no definitive trend among alerting criteria in terms of "incident resolution" versus runway spacing. Incident resolution tends to increase between the 1,700 and 2,000 ft runway spacings and then decreases for the 2,500 and 3,400 foot spacings. Improvement in incident resolution from 1,700 to 2,000 ft runway spacings is a

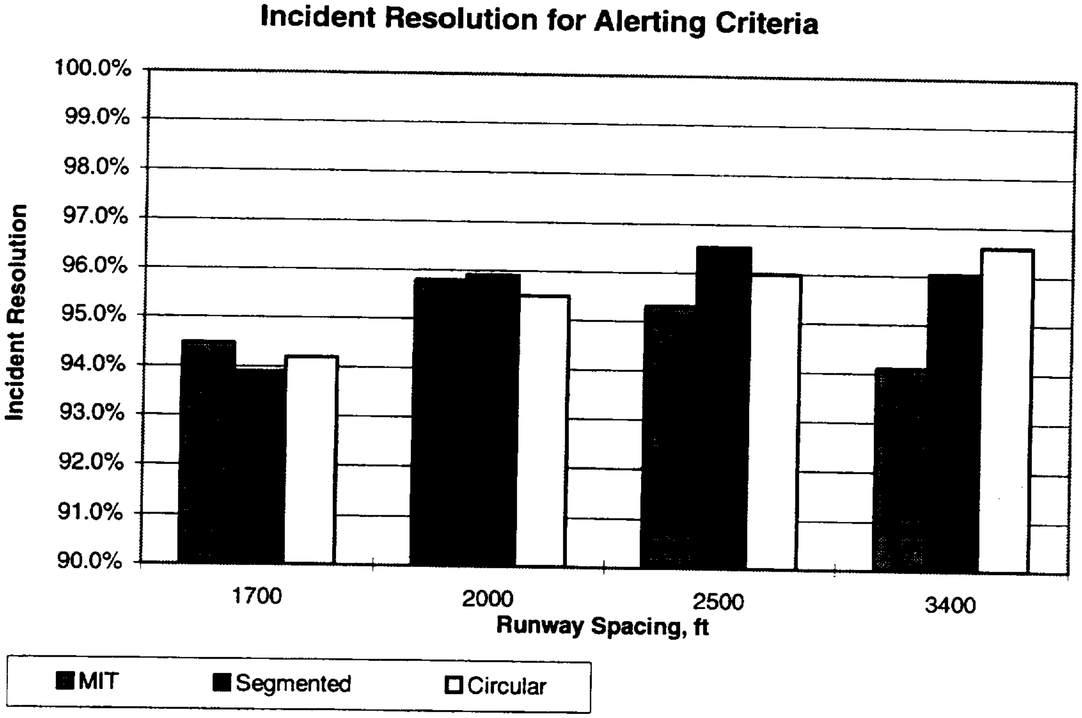


Figure 5-1 Incident Resolution for AILS Alerting Systems
(CT: σ=327 ft; LT: +/-3,000 ft; P/A: σ=5 sec Rayleigh; ~2 Hz; no data uncertainty; no link failures; evasive maneuver=30° bank to 40° heading+ with no climb)

direct result of increased detection time for the intruder to reach the evader runway. Due to the fixed prediction time ($t_{predict}$ = 20 sec), spacings above 2,000 ft do not benefit from the increased intercept time.

At the larger runway spacings, the intruder is flying a straight path toward the evader when it crosses the time prediction threshold. Apparently, the time prediction is more conservative when the intruder is turning as compared to flying a direct path toward the evader, and consequently, the time to intercept for the straight path is underestimated, thus reducing the incident resolution for the larger runway spacings.

Note: The evasive maneuver is a turn away form the intruder using a 40° heading. In the event the intruder blunder exceeds 40° heading, the evasive maneuver is increased to exceed intruder heading by 5°. This is denoted by the "+", indicating an evasive maneuver with adaptive turning capability. For Figure 5-1 no climbing component was included in the evasive maneuver.

Figure 5-2 compares the false alarm performance of the AILS alerting system candidates. Segmented alerting has significantly lower false alarm rates at all four runway spacings. This is because segmented alerting, as implemented, places constraints on worst case blunder

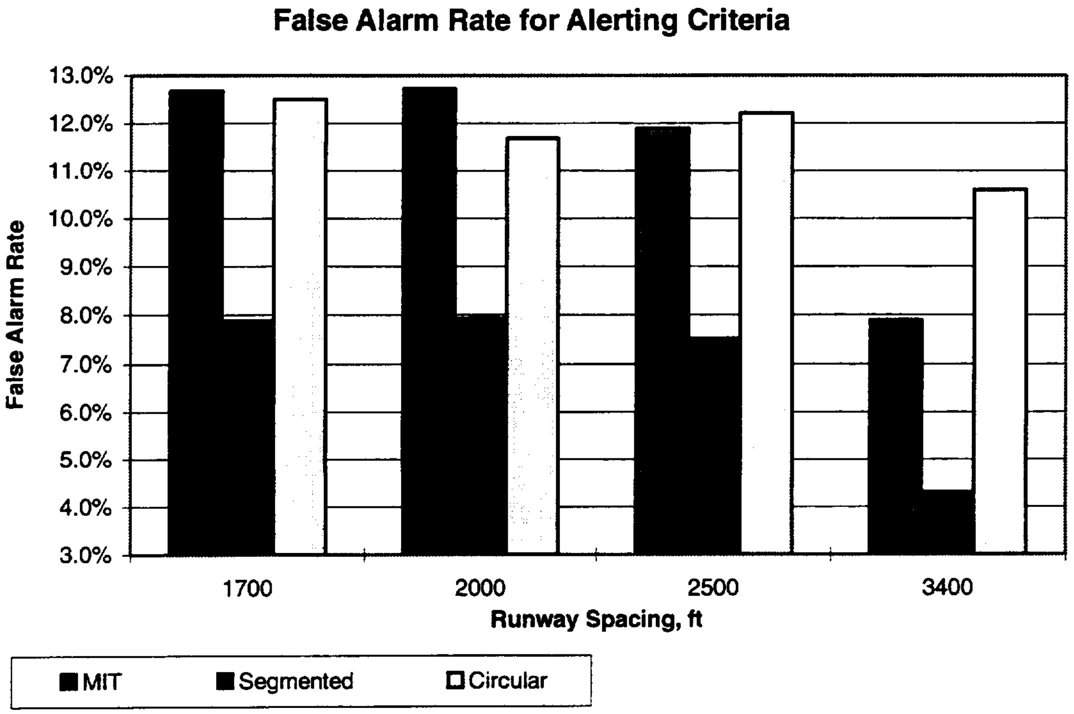


Figure 5-2 False Alarm Rates for AILS Alerting Systems
(CT: σ=327 ft; LT: +/-3,000 ft; P/A: σ=5 sec Rayleigh; ~2 Hz; no data uncertainty; no link failures; evasive maneuver=30° bank to 40° heading+ with no climb)

headings to ~ 30°. MIT and Circular alerting do not place such constraints on blunder headings and thus are more vulnerable to false alarms.

An important case of false alarm performance is "normal approach" false alarms; results are shown in Figure 5-3. Recall that "normal approach" false alarms refers to false alarms that occur when both the evader and intruder aircraft are performing normal approaches. This of course is highly undesirable. The MIT algorithm had the fewest number of "normal approach" false alarms, closely followed by Segmented alerting. Circular alerting exhibits a relatively higher rate of "normal approach" false alarms, approaching 0.8% of approaches flown at 1,700 ft runway spacings. At 2,500 ft runway spacings or greater none of the alerting systems experienced any "normal approach" false alarms.

Another important aspect of false alarm performance is "near miss" false alarms, i.e., false alarms that occur for close miss distances that are not considered an incident (CPA < 1,000 ft). A high percentage of "near miss" false alarms indicates good alerting accuracy. Figure 5-4 shows "near miss" false alarm performance. Both, MIT and Segmented alerting exhibit a high percentage of "near miss" false alarms, with Segmented alerting having a slight edge at the 2,500 foot runway spacing. Circular alerting has a very low percentage of "near miss" false alarms indicating relatively poor alerting performance.

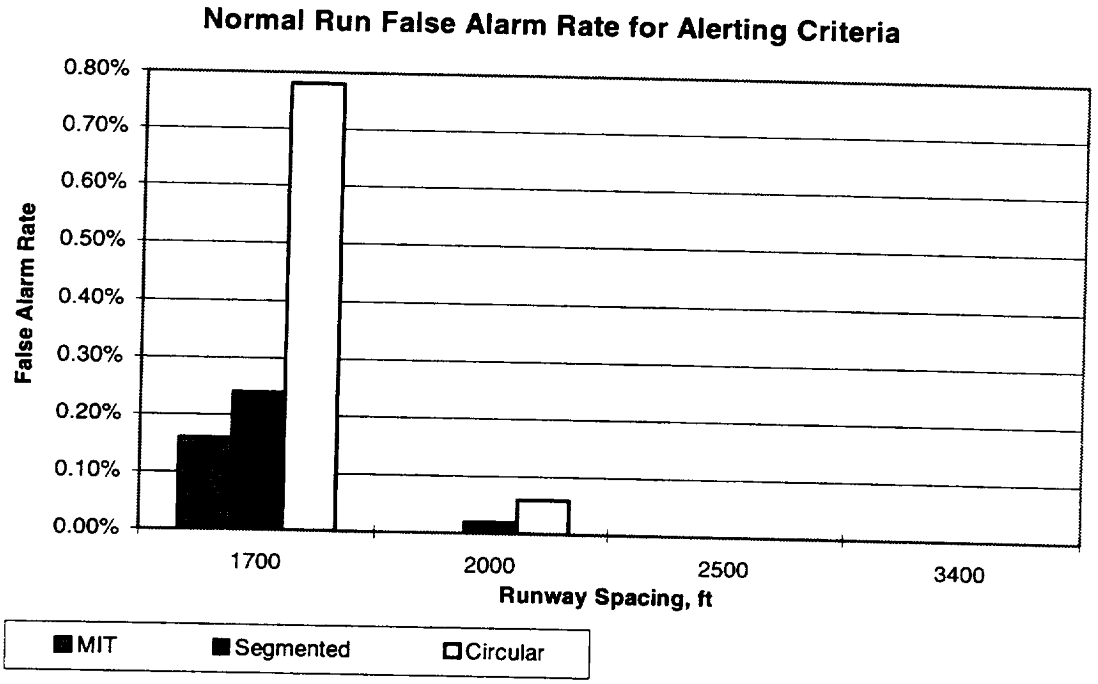


Figure 5-3 Normal Run False Alarm Rate
(CT: σ=327 ft; LT: +/-3,000 ft; P/A: σ=5 sec Rayleigh; ~2 Hz; no data uncertainty; no link failures; evasive maneuver=30° bank to 40° heading+ with no climb)

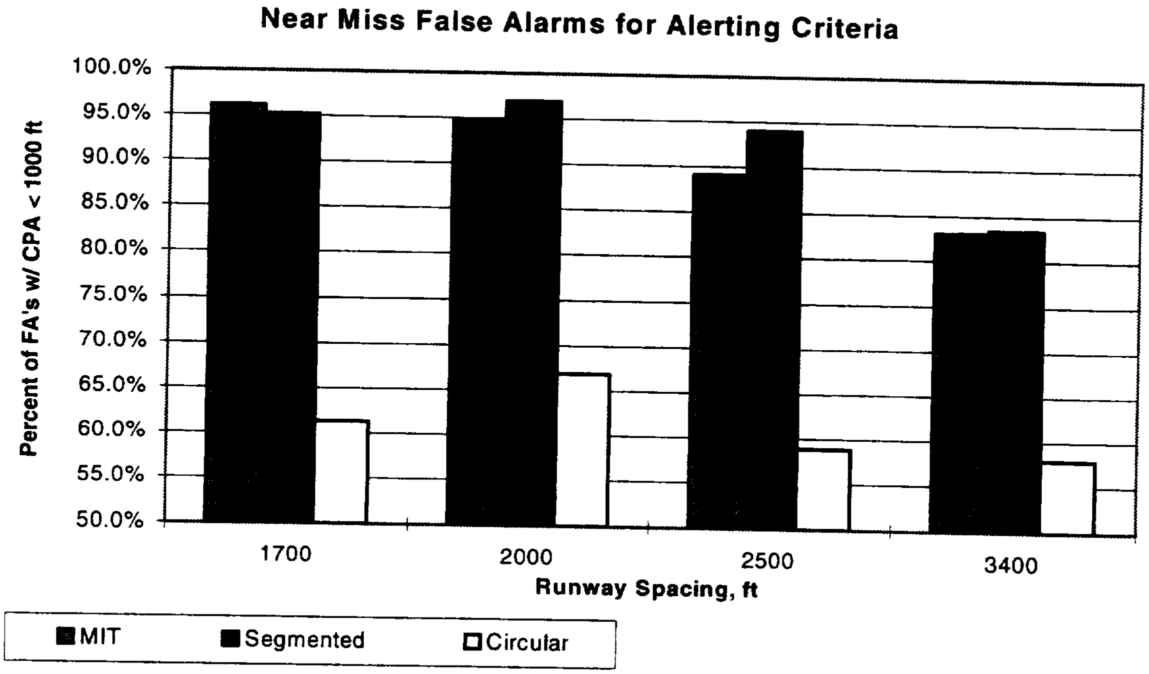


Figure 5-4 Near Miss False Alarm Rate
(CT: σ=327 ft; LT: +/-3,000 ft; P/A: σ=5 sec Rayleigh; ~2 Hz; no data uncertainty; no link failures; evasive maneuver=30° bank to 40° heading+ with no climb)

5.3 Segmented Alerting System Performance

The remainder of section 5 discusses alerting system performance for the Segmented alerting system.

5.3.1 Segmented Alerting Performance as a Function of Blunder Type

Figures 5-5 and 5-6 indicate the incident resolution and false alarm performance of Segmented alerting as a function of blunder type. Four blunder scenarios are considered; 1) a 30° heading blunder (worst case blunder), 2) a 15° heading blunder, 3) a slow 5° heading blunder, and 4) a constant 5° bank angle blunder.

From Figure 5-5 alerting performance is poor for the 30° heading blunder for runway spacings below 2,500 ft. At runway spacings less than 2,500 feet the alerting algorithm does not allow enough time to evade a 30° heading blunder. Performance improves significantly at runway spacings of 2,500 feet or greater, since the evader has sufficient time to react.

At close runway spacings, increasing the prediction time is not expected to improve performance since pilot/aircraft response time typically exceeds time to incident.

Alerting performance for the remaining blunders is considerably better. Performance for both the 15° heading and the 5° bank angle blunder slowly degrade with increasing runway spacing. As mentioned earlier, performance degrades when the intruder flies a straight path toward the evader, as is the case for larger runway spacings.

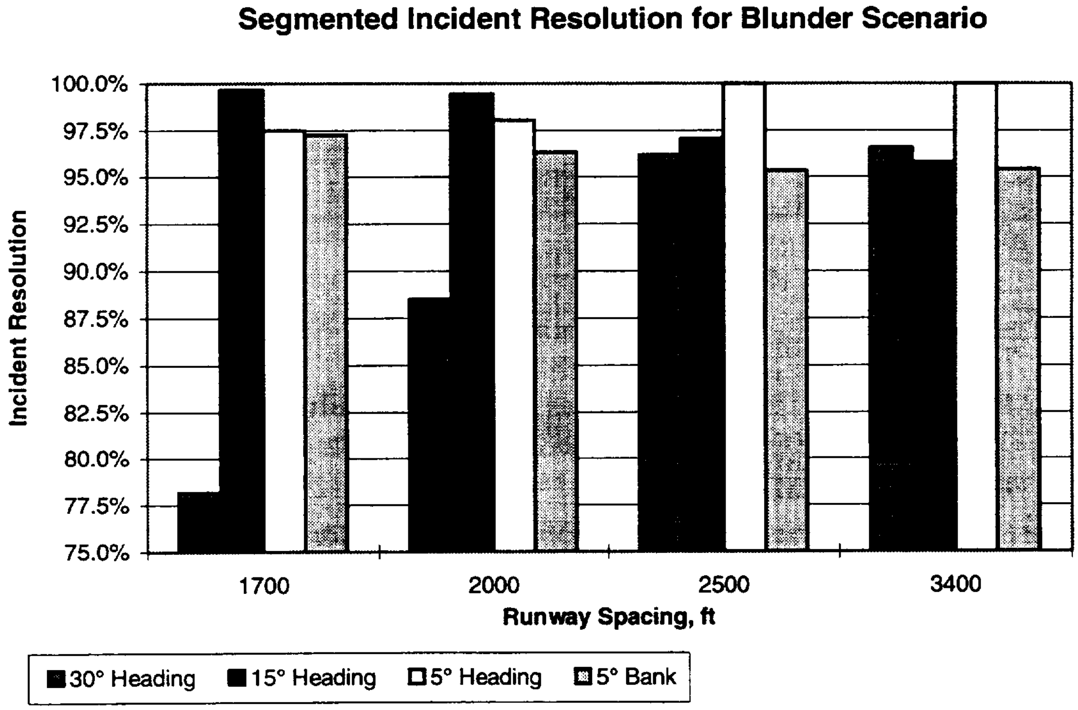


Figure 5-5 Incident Resolution as a Function of Blunder Type
(CT: σ=327 ft; LT: +/-3,000 ft; P/A: σ=5 sec Rayleigh; ~2 Hz; no data uncertainty; no link failures; evasive maneuver=30° bank to 40° heading+ with no climb)

Performance for the 5° heading blunder improved with increased runway spacing. This maybe misleading due to a limited number of potential incidents that occurred for this slow blunder, i.e., a small sample space exists.

Figure 5-6 indicates false alarm performance for Segmented alerting as a function of blunder type. From Figure 5-6, false alarm rate is higher for the less aggressive blunders. For intruders with small angles of incidence, slight changes in the flight path can cause relatively large changes in the predicted along track intercept; these large changes tend to result in a larger number of false alarms.

With the exception of the 5° heading blunder, the false alarm rates were reasonably flat with respect to runway spacing. The 5° heading blunder false alarm rate decreased for greater runway spacing because the number of potential incidents drop, i.e. the track duration was not long enough to reach the other runway for a large percentage of the time.

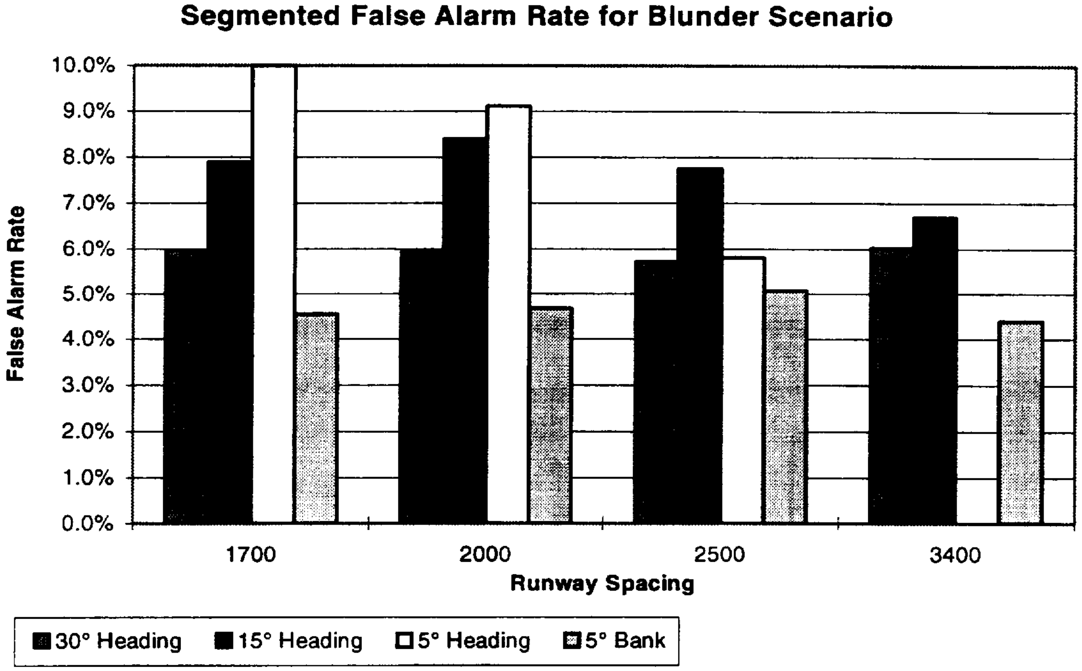


Figure 5-6 False Alarm Rate as a Function of Blunder Type
(CT: σ=327 ft; LT: +/-3,000 ft; P/A: σ=5 sec Rayleigh; ~2 Hz; no data uncertainty; no link failures; evasive maneuver=30° bank to 40° heading+ with no climb)

5.3.2 Alerting Performance as a Function of Cross-Track Distribution

Cross-track distributions were tested that simulate manual ILS, manual DGPS, and autopilot DGPS approaches (i.e., Total System Errors, TSEs). Figures 5-7 and 5-8 show incident resolution and false alarm performance for Segmented alerting as a function of the approach / landing type (cross-track distribution).

For TSEs as large as a manual, ILS (1/2 dot FTE) approach, the cross-track distribution of the two approach aircraft did not significantly affect the performance of the Segmented alerting algorithm. Incident resolution increased slightly with decreasing cross-track offsets. False alarm rates remain flat independent of cross-track distribution.

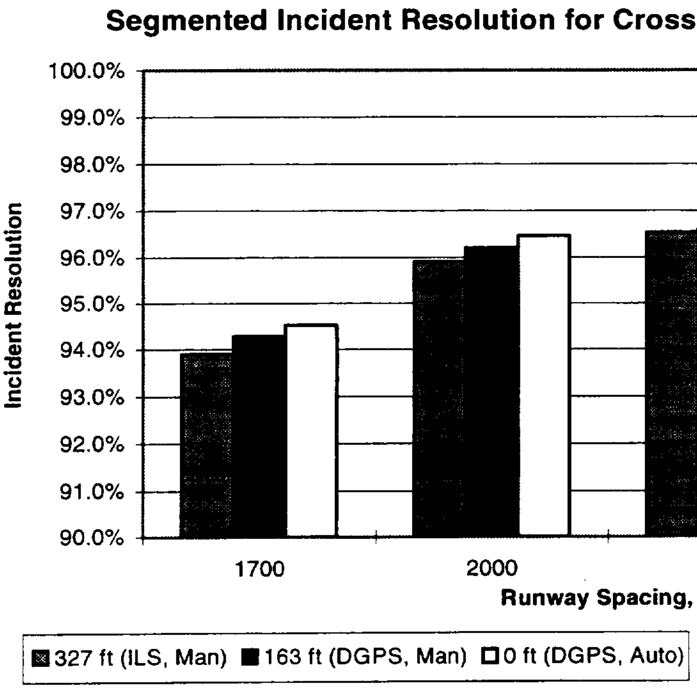


Figure 5-7 Incident Resolution as a Function of Cross-Track Distribution
(CT: σ=X ft; LT: +/-3,000 ft; P/A: σ=5 sec Rayleigh; ~2 Hz; no data uncertainty; no link failures; evasive maneuver=30° bank to 40° heading+ with no climb)

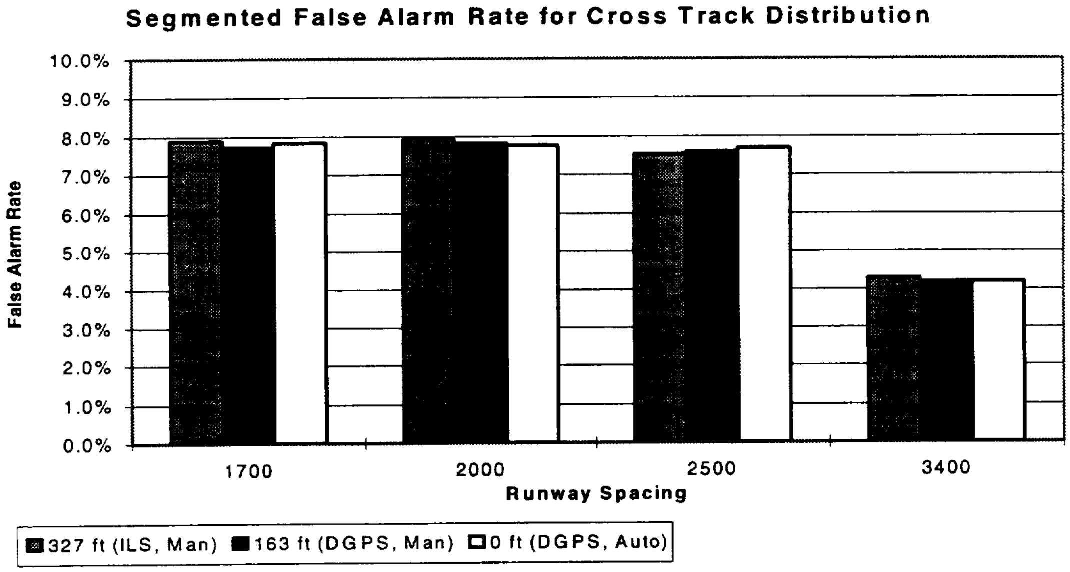


Figure 5-8 False Alarm Rate as a Function of Cross-Track Distribution
(CT: σ=X ft; LT: +/-3,000 ft; P/A: σ=5 sec Rayleigh; ~2 Hz; no data uncertainty; no link failures; evasive maneuver=30° bank to 40° heading+ with no climb)

5.3.3 Alerting Performance as a Function of (State Variable) Data Uncertainty

State variable "uncertainty" based on available and/or expected future avionics sensors were simulated and compared to the ideal system (no uncertainty). AHRS, IRS, and GPS sensor performance for providing the appropriate AILS state variables was considered. Table 5-2 summarizes ARINC specifications for these sensors. Figures 5-9 and 5-10 show incident resolution and false alarm performance of Segmented alerting for the various sensors, respectively.

From Figure 5-9 it is evident that with AHRS absolute accuracies (ARINC 705), the incident resolution is significantly reduced as compared to the ideal system. Track angle accuracy (+/- 6°) is the dominant factor in reducing performance. With GPS absolute accuracies (ARINC 743), the incident resolution is only slightly degraded as compared to the ideal system.

As indicated in Figure 5-10, false alarm rates are not significantly affected by data uncertainty. Given the current ARINC specifications and the results of this simulation, GPS accuracy will be required to perform parallel approaches at closely spaced parallel runways.

Parameter	ARINC Label	System	# bits	Range	Resol.	Accuracy [1],[2],[3]	Noise (1σ) [4]	Update Rate (Hz)	Filter BW (Hz)
Roll	325	AHRS IRS	15	+/- 180°	0.0055°	0.1°	0.03°	50	8
Track Angle-mag	317	AHRS IRS	15	+/-180°	0.0055°	+/- 6°	0.04°	20	2
Ground Speed	312	AHRS IRS	15	4096 knots	0.125 knots	+/- 12 knots	0 knots	20	2
Position-lat	110/120	DGPS			0.031 feet	10 m	1.5 m	1	NF
Position-long	111/121	DGPS			0.031 feet	10 m	1.5 m	1	NF
Track Angle-true	313	IRS	15	+/- 180°	0.0055°	+/- 5°	0.02°	20	2
Heading-true	314	IRS	15	+/- 180°	0.0055°	+/- 4°	0.02°	20	2
Heading-mag	320	AHRS IRS	15	+/- 180°	0.0055°	+/- 2°	0.04°	20	2
Track Angle-true	103	GPS	15	+/-180°	0.0055°	+/- 1°		1	NF
Ground Speed	112	GPS	15	4096 knots	0.125 knots	+/- 2 knots		1	NF

[1] AHRS / IRS accuracies listed in ARINC 704A specification.

[2] GPS accuracies derived by in-house experts.

[3] GPS track angle accuracy derived by dividing GPS ground speed accuracy by the ground speed, ta_acc = v_acc / v

[4] Measured using actual sensor data

Table 5-2 Summary of ARINC Sensor Specifications

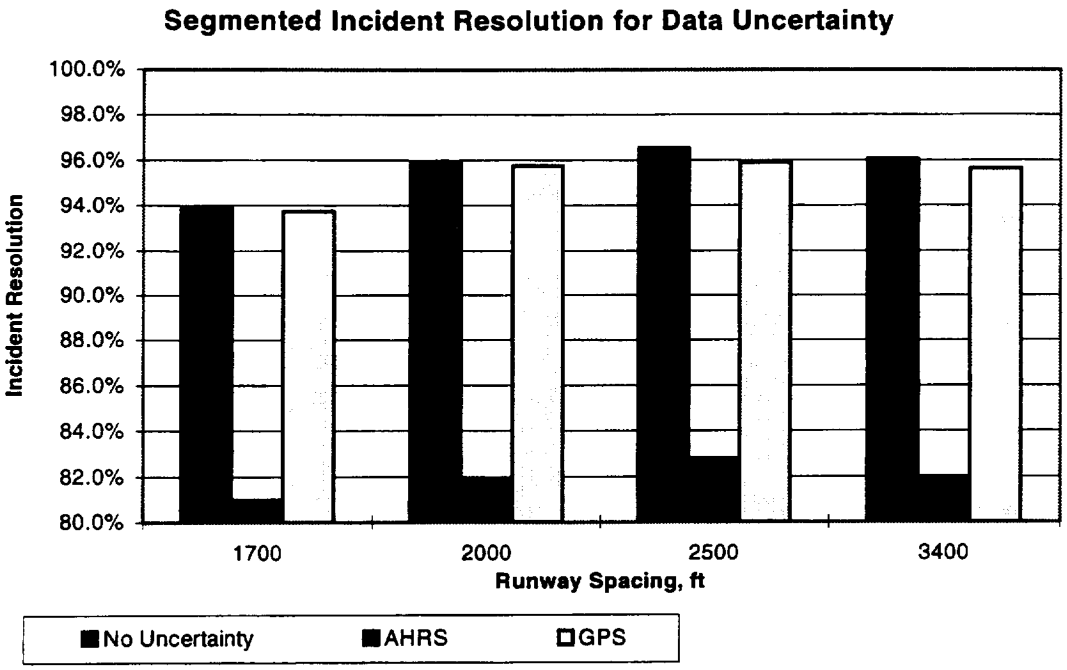


Figure 5-9 Incident Resolution as a Function of Sensor Accuracy
(CT: σ=327 ft; LT: +/-3,000 ft; P/A: σ=5 sec Rayleigh; ~2 Hz; X data uncertainty; no link failures; evasive maneuver=30° bank to 40° heading+ with no climb)

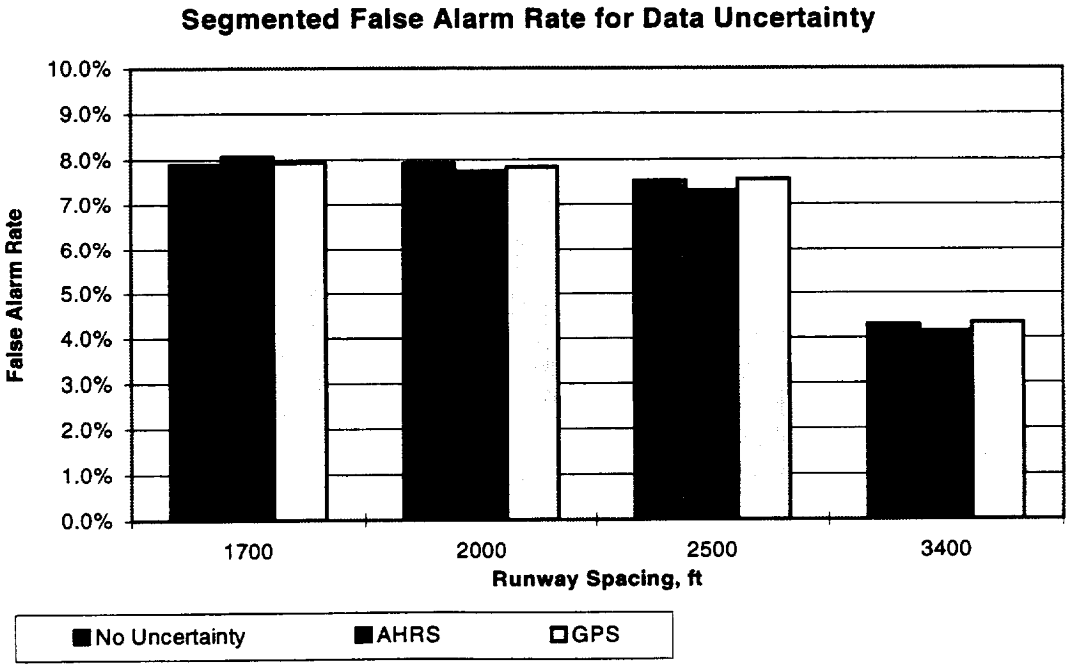


Figure 5-10 False Alarm Rate as a Function of Sensor Accuracy
(CT: σ=327 ft; LT: +/-3,000 ft; P/A: σ=5 sec Rayleigh; ~2 Hz; X data uncertainty; no link failures; evasive maneuver=30° bank to 40° heading+ with no climb)

5.3.4 *Alerting Performance as a Function of Data Update Rate*

This section considers alerting performance as a function of state variable data update rate. While the bulk of simulations were run at ~2 Hz update rates, reductions in data update rate were considered since it is desirable to mitigate their impact on avionics sensors and data links. Rate reductions to 1 Hz and 0.5 Hz were considered. Figures 5-11 and 5-12 show incident resolution and false alarm rates for Segmented alerting as a function of update rate, respectively.

As expected, incident resolution decreases for lower update rates since blunder detection is delayed. Degradation from 2 Hz to 1 Hz updates is minor. However, degradation from 2 Hz to 0.5 Hz updates becomes significant. 1 Hz update rates appear sufficient for AILS Segmented alerting. From Figure 5-12 false alarm rates are not significantly affected by update rate.

5.3.5 *Alerting Performance as a Function of Communication Link Failure*

Figures 5-13 and 5-14 show incidence resolution and false alarm rate performance of Segmented alerting as a function of communication link failure rate, respectively. The significance of link failures is that AILS state variable data are not updated at the typical update rate. Data link communication failure rates of 0%, 10%, and 20% were simulated.

During a link failure, the alerting system interpolates the state variables from the previous sample. From Figures 5-13 and 5-14 it is evident that for the link failure rates that were simulated, incident resolution did not degrade significantly. Incident resolution actually increased slightly in some cases in the presence of link failures. This result is counter-intuitive. However, interpolation is a smoothing process which could result in quicker blunder detection for cases where state variables are noisy.

Link failure rates up to 10% do not appear to be a factor in alerting performance. Probability for three consecutive communications being lost are 0.1% and 1% for 10% and 20% link failure rates, respectfully.

False alarm rates are not significantly affected by link failures.

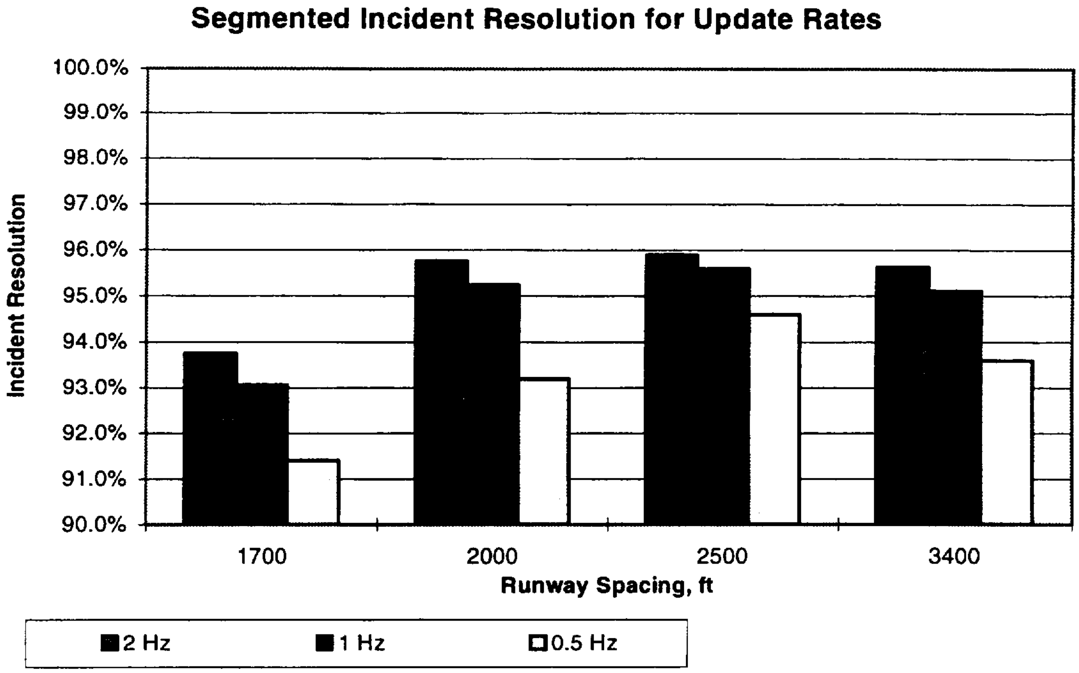


Figure 5-11 Incident Resolution as a Function of Data Update Rate
(CT: σ=327 ft; LT: +/-3,000 ft; P/A: σ=5 sec Rayleigh; ~X Hz; GPS data uncertainty; no link failures; evasive maneuver=30° bank to 40° heading+ with no climb)

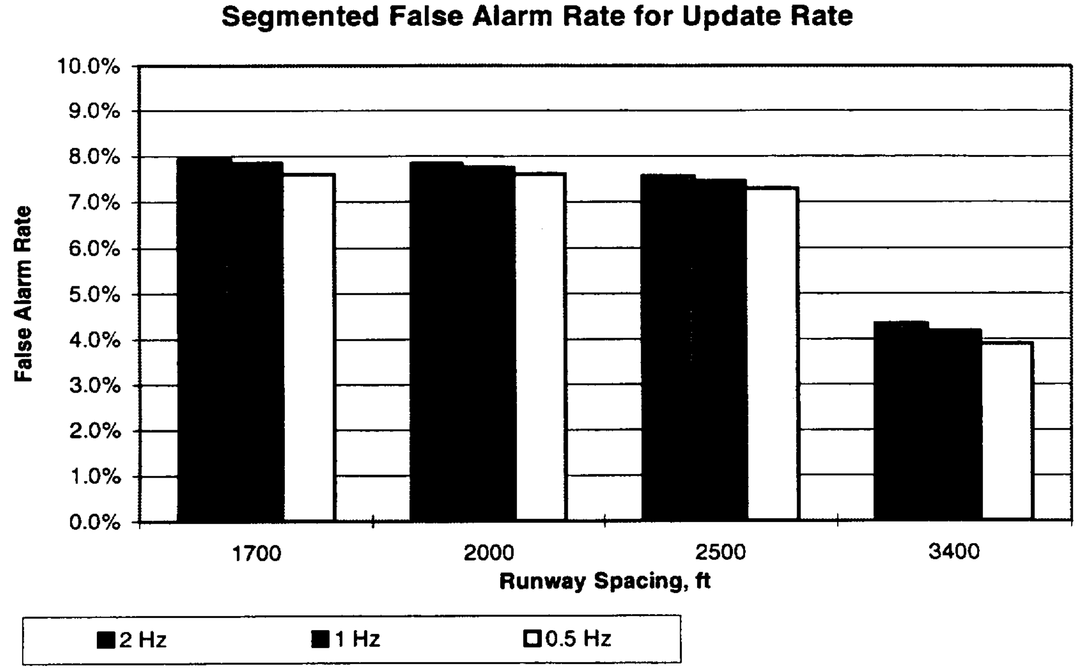


Figure 5-12 False Alarm Rate as a Function of Data Update Rate
(CT: σ=327 ft; LT: +/-3,000 ft; P/A: σ=5 sec Rayleigh; ~X Hz; GPS data uncertainty; no link failures; evasive maneuver=30° bank to 40° heading+ with no climb)

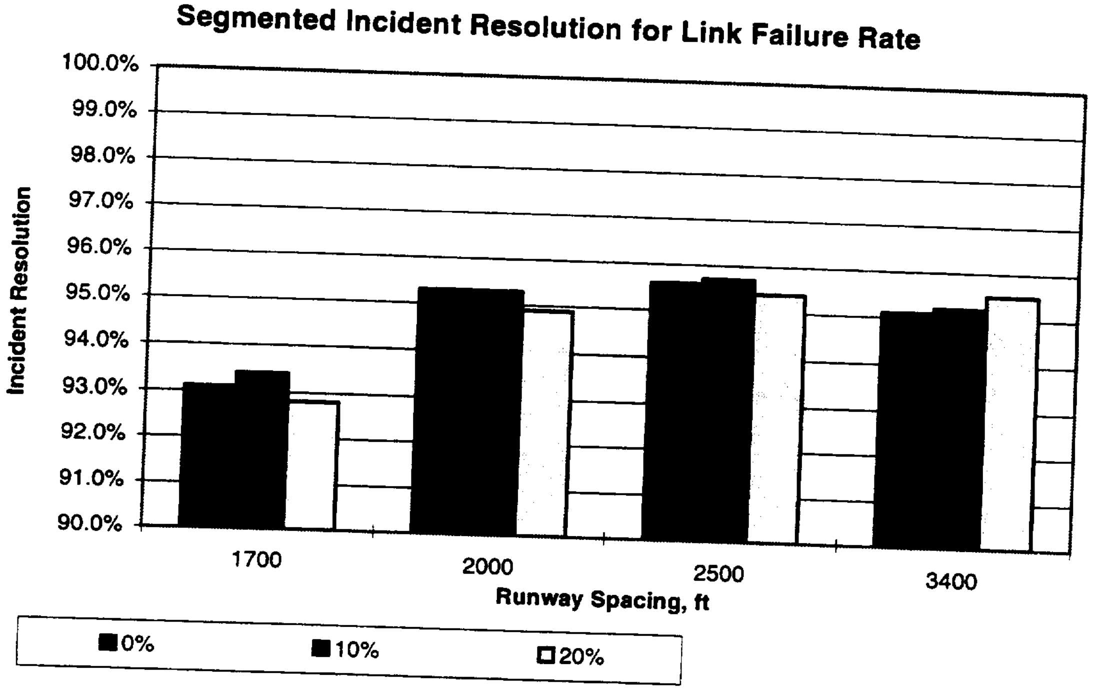


Figure 5-13 Incident Resolution as a Function of Link Failure Rate
(CT: σ=327 ft; LT: +/-3,000 ft; P/A: σ=5 sec Rayleigh; ~1 Hz; GPS data uncertainty; X link failures; evasive maneuver=30° bank to 40° heading+ with no climb)

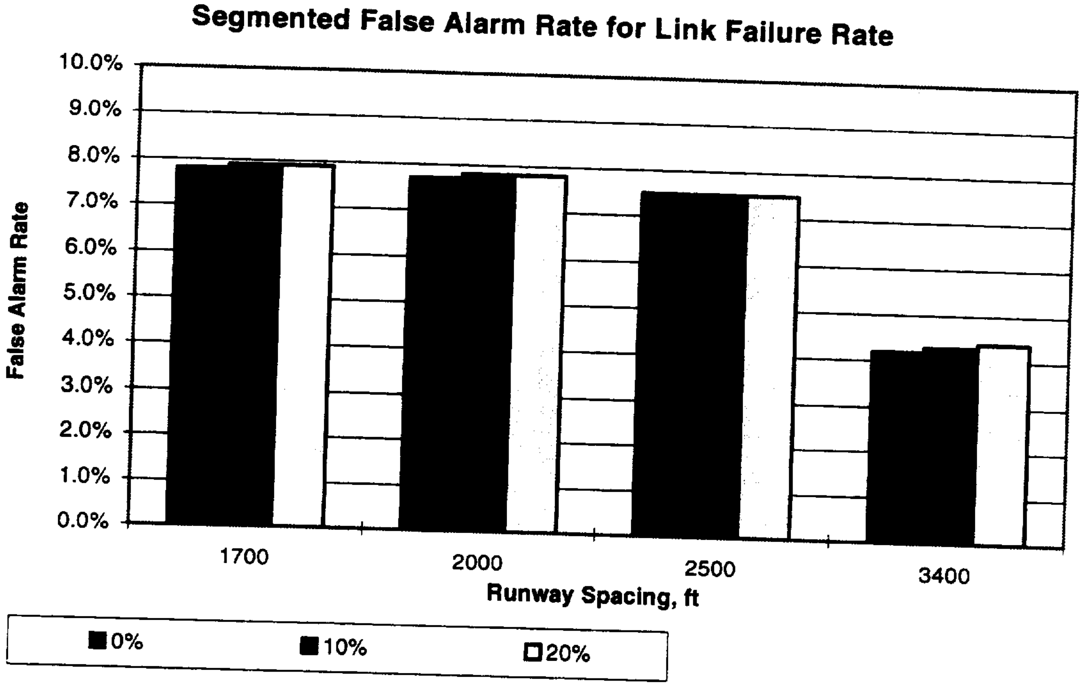


Figure 5-14 False Alarm Rate as a Function of Link Failure Rate
(CT: σ=327 ft; LT: +/-3,000 ft; P/A: σ=5 sec Rayleigh; ~1 Hz; GPS data uncertainty; X link failures; evasive maneuver=30° bank to 40° heading+ with no climb)

5.3.6 Alerting Performance as a Function of Pilot / Aircraft Response Time

Both fixed and distributed pilot / aircraft response times were simulated. For fixed response time simulations, the pilot / aircraft always responded in exactly X seconds; 5 and 10 second times were simulated. For distributed response simulations, the response time was determined by a Rayleigh probability distribution (σ=5 sec, 99% of response times are less than 15 sec).

Figures 5-15 and 5-16 show incident resolution and false alarm performance for Segmented alerting as a function of pilot / aircraft response time, respectively. From Figure 5-15 it is evident that pilot / aircraft response time significantly impacts performance of the alerting system. 10 second fixed response times yield relatively poor performance. 5 second fixed response times yield exceptional performance. Rayleigh distributed response times yield average performance, where response times greater than 5 seconds limit performance. As seen in Figure 5-15, response time is critical at lowest runway spacings.

If we could guarantee less than 5 second pilot / aircraft response times, we could easily meet our alerting performance goals at 2,000 ft runway spacings and very nearly meet our goals at 1,700 ft. NASA flight simulator experiments using subject pilots should provide important feedback in this area.

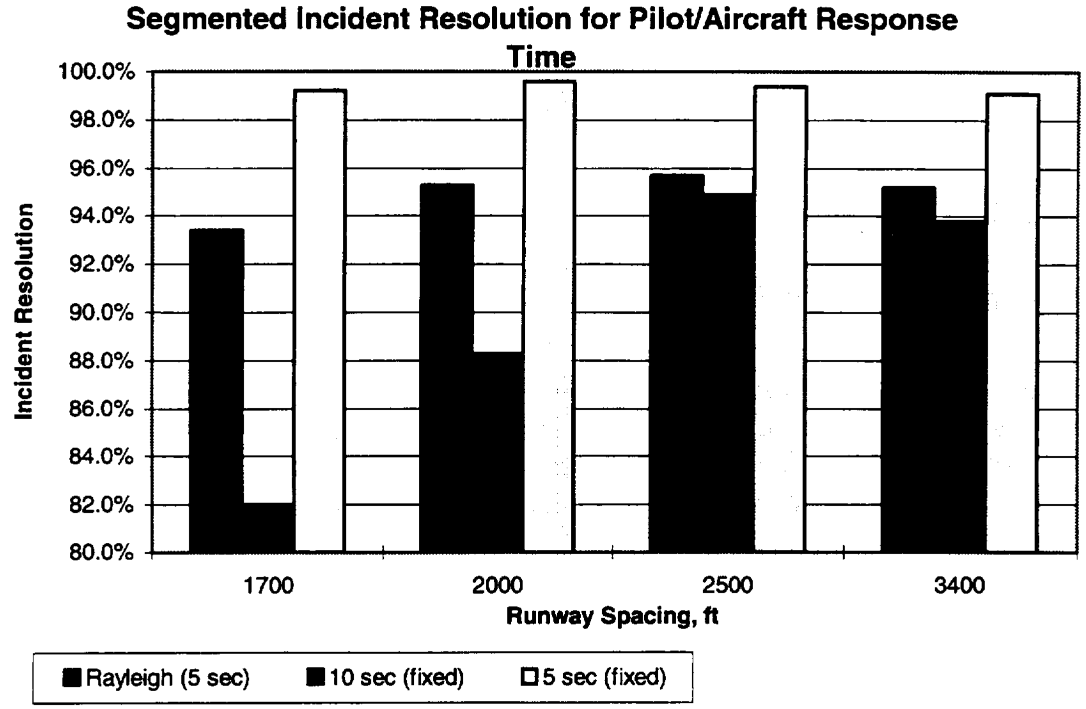


Figure 5-15 Incident Resolution as a Function of Pilot / Aircraft Response Time
(CT: σ=327 ft; LT: +/-3,000 ft; P/A: X response time; ~1 Hz; GPS data uncertainty; 10% link failures; evasive maneuver=30° bank to 40° heading+ with no climb)

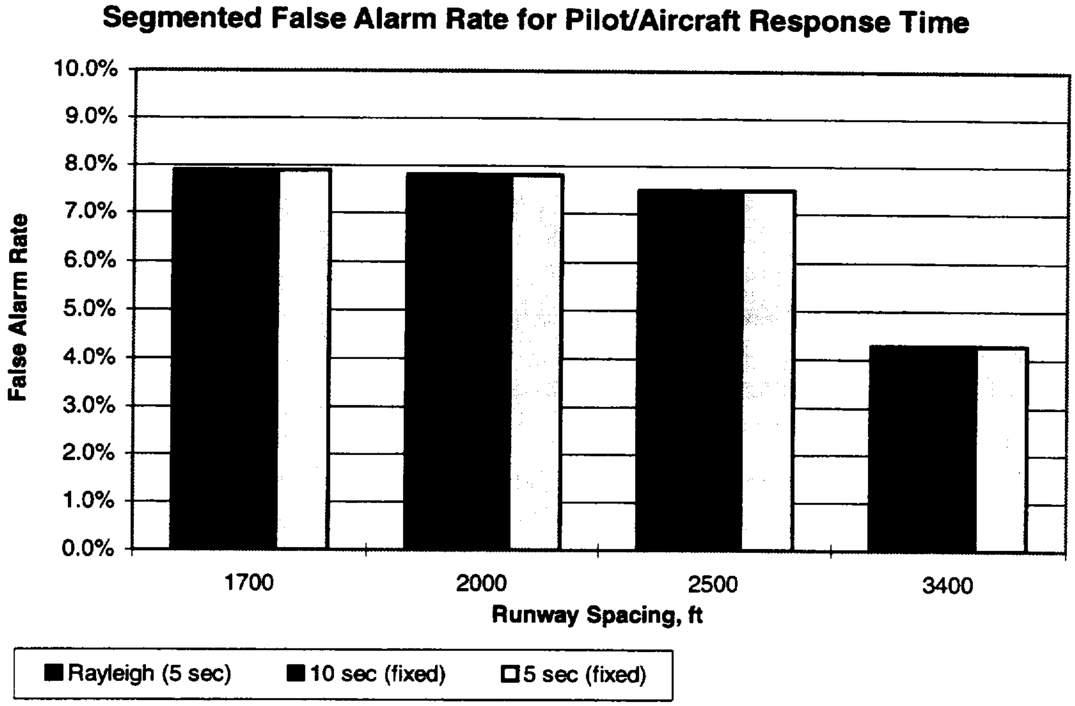


Figure 5-16 False Alarm Rate as a Function of Pilot / Aircraft Response Time
(CT: σ=327 ft; LT: +/-3,000 ft; P/A: X response time; ~1 Hz; GPS data uncertainty; 10% link failures; evasive maneuver=30° bank to 40° heading+ with no climb)

5.3.7 Alerting Performance versus Type of Evasive Maneuver

Three basic evasive maneuvers were simulated: 1) a 30° bank to a 40° heading, 2) a 30° bank to 40° heading or 5° greater than intruder blunder heading (whichever is greater), and 3) a 30° bank to 40° heading or 5° greater than intruder with a 2,000 ft/min, 0.25 g climb.

The type of evasive maneuver significantly impacts alerting performance. The scripted maneuver using a 30° bank to a 40° heading is least effective. Performance with this maneuver decreases with runway spacing due to induced incidents nearly 1 minute after the start of the evasive maneuver. As illustrated in Figure 5-17, the evader evasive maneuver is inadequate to avoid the intruder, who eventually can catch up to the evader. (Note: Figure 5-17 does not utilize a climb component in the evasive maneuver and the entire scenario could be occuring at co-altitude).

In order to overcome this type of scenario, the evasive maneuver was amended to include an adaptive turn/heading component. A 30° bank with an adaptive heading performed better than the scripted maneuver, eliminating induced incidents.

The 30° bank to an adaptive heading with an altitude climb performs much better than either of the previous two evasive maneuvers. Use of an altitude evasive maneuver may significantly improve the performance of the alerting systems, but will require altitude tracking. Use of the altitude dimension was not addressed in this AILS study and will require further study.

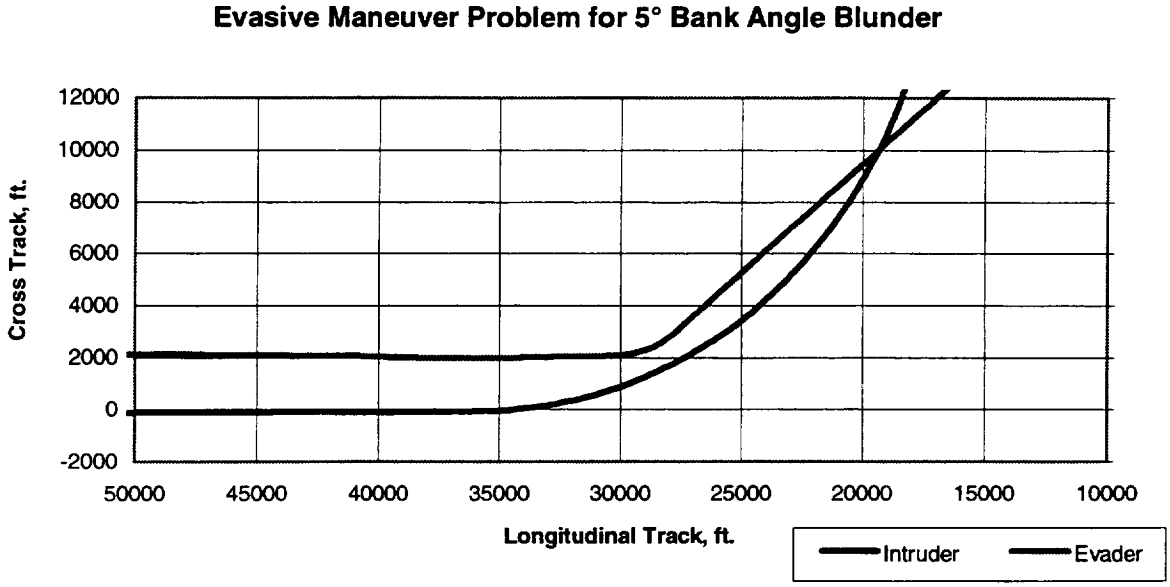


Figure 5-17 Example #1 of an Induced Incident
(evasive maneuver=30° bank to 40° heading with no climb)

Another interesting example of an induced incident is illustrated in Figures 5-18 and 5-19. Figure 5-18 shows a lateral plan view perspective of how a late alert can result in an induced incident even with an evasive maneuver. The 15° heading blunder appears to miss just outside the 500 ft protection volume until late in the scenario, when an alert is finally issued. From the altitude perspective seen in Figure 5-19, the intruder actually levels off above the evader and would not cause an incident. However, since an alert was issued, the evader takes evasive action and actually climbs back into the intruders path, inducing an incident. Fortunately, the number of induced scenarios of this type are few even for a large number of Monte Carlo simultions. This example requires further study.

Figures 5-20 and 5-21 illustrate incident resolution and false alarm performance for Segmented alerting for several types of evasive maneuvers, respectively. From Figure 5-20, the type of evasive maneuver has considerable influence on incident resolution. The evasive maneuver, utilizing a 2,000 ft/min (33.3 ft/sec) climb rate provides the best performance. False alarm performance was not affected by the evasive maneuvers that were considered.

Note: As indicated previously, this AILS alerting study was primarily focused on performing the alerting function without regard to altitude, i.e., both aircraft in the same glideslope plane. This assumption greatly simplified the study and also provides a worst case test if both evader and intruder aircraft are assumed co-altitude at all times. As the study neared its conclusion, we briefly examined the possibilities of using an evasive maneuver that includes a climb component. The use of a climb maneuver may provide significant improvements in alerting performance for some blunders. However, scrutiny of the altitude behavior of the intruder aircraft during the blunder is required. In some scenarios, an evasive maneuver with a climb component will not be able to take full advantage of the climb. Further study is required to assess climb evasive maneuvers.

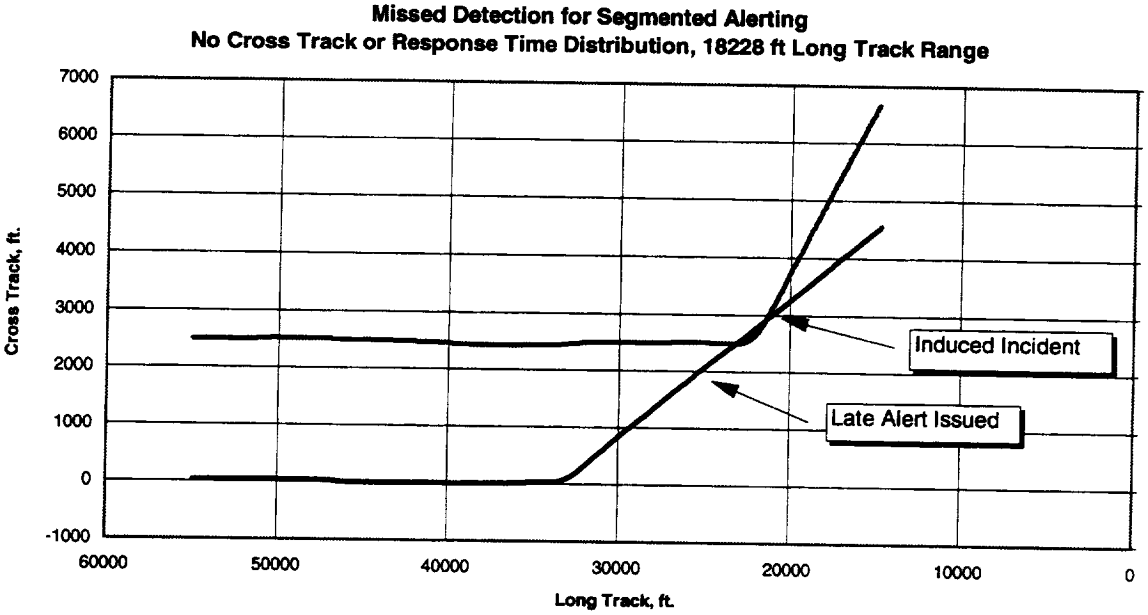


Figure 5-18 Example #2 of an Induced Incident (Plan View)
(evasive maneuver=30° bank to 40° heading+ with a 2,000 ft/min climb)

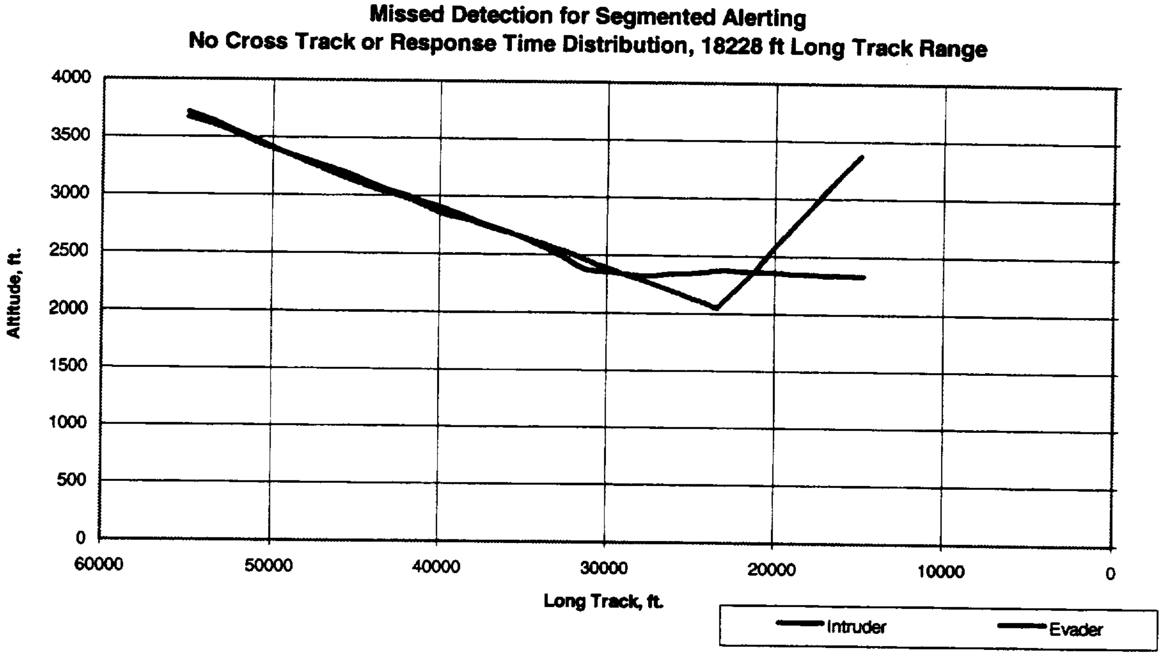


Figure 5-19 Example #2 of an Induced Incident (Altitude View)
(evasive maneuver=30° bank to 40° heading+ with a 2,000 ft/min climb)

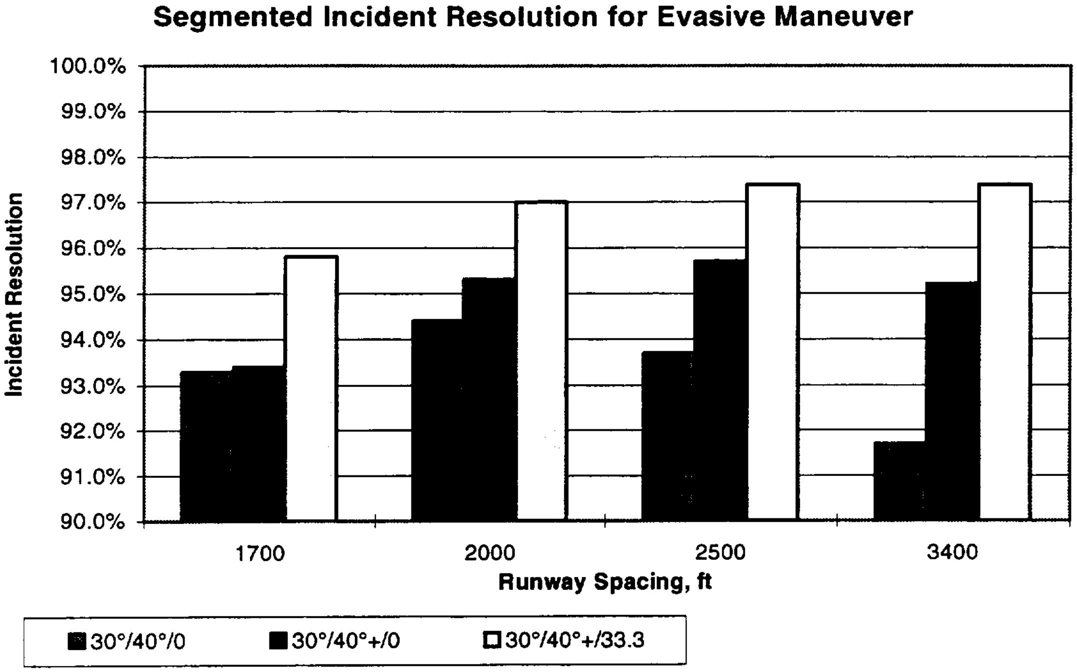


Figure 5-20 Incident Resolution for Several Types of Evasive Maneuvers
(CT: σ=327 ft; LT: +/-3,000 ft; P/A: σ=5 sec Rayleigh; ~1 Hz;
GPS data uncertainty; 10% link failures; X evasive maneuvers)

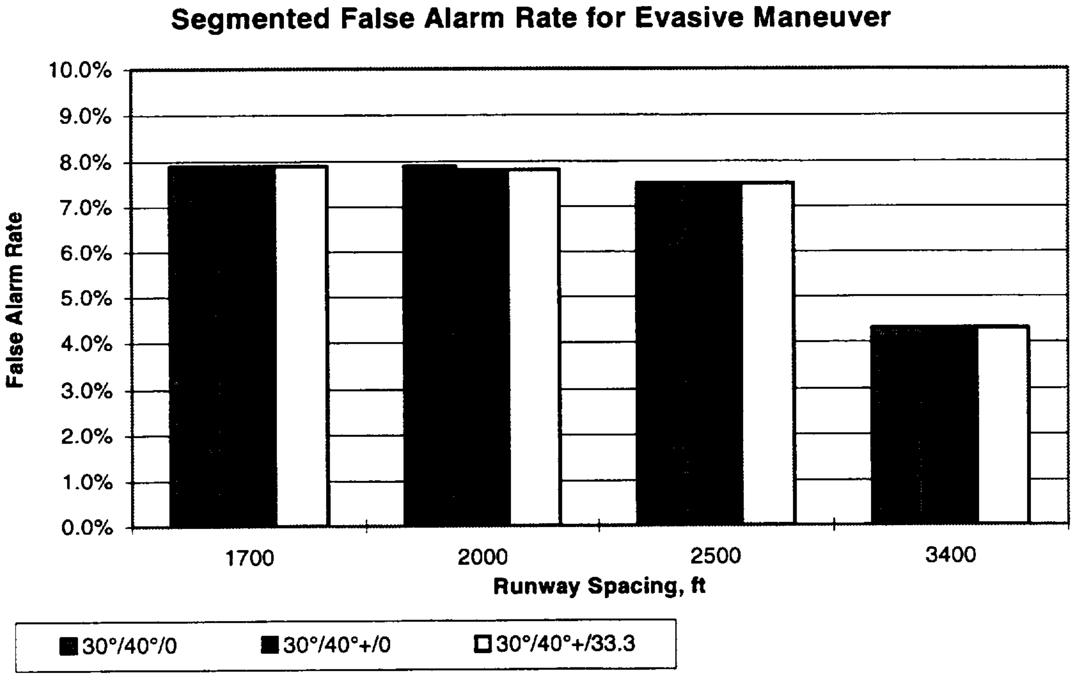


Figure 5-21 False Alarm Rate for Several Types of Evasive Maneuvers
(CT: σ=327 ft; LT: +/-3,000 ft; P/A: σ=5 sec Rayleigh; ~1 Hz;
GPS data uncertainty; 10% link failures; X evasive maneuvers)

5.4 AILS Alerting Performance - Summary

AILS alerting performance is strongly dependent on the assumed "distributions" used in the simulations, with pilot / aircraft response time being a primary factor affecting achievable runway spacings.

The following summarizes AILS alerting performance for non-ideal distributions and using a turn and climb evasive maneuver:

Incident Resolution:	~ 95% of all blunders
False Alarms:	~7% Segmented alerting, ~13% MIT alerting
"Normal Approach" false alarms:	
	0.1 - 0.2% for 1700 ft runway spacings,
-	0 for 2500 ft runway spacings
"Near Miss" False Alarms:	90-95% of all false alarms, indicating good alerting accuracy.

2500 ft appears to be the minimum allowable runway spacing due to the severity of the 30° heading blunder (assumes Rayleigh pilot / aircraft response times with $\sigma = 5$ sec).

Cross-track errors, i.e., TSEs, do not greatly affect alerting performance.

GPS sensor accuracies will be required for AILS alerting particularly for providing ground track heading.

1 Hz data update rates and 10% to 20% link failure rates are sufficient for AILS alerting.

6. Sensor Requirements

Core AILS state variable data to be monitored for the evader and intruder aircraft are aircraft position (latitude, longitude and altitude), bank angle / roll, true track / ground heading, and ground speed. Typical aircraft sensor that provide this information are the Inertial Reference System (IRS), the Attitude Heading Reference System (AHRS), and GPS. Table 5-2 (page 5-8) summarizes the achievable accuracies and resolution of AILS state variable data as provided by ARINC specifications.

Based on Monte Carlo simulation of sensor uncertainties (section 5.3.3) it was determined that true track / ground heading accuracies provided by AHRS and IRS are inadequate due to the +/- 6° accuracy provided by these sensors. GPS provides +/- 1° true track / ground heading accuracy which is sufficient for the AILS Segmented alerting algorithm.

AHRS and IRS bank angle / roll data is provided to 0.1° accuracy at 50 Hz update rates which is more than sufficient for AILS alerting.

GPS position accuracy of 10 meters and ground speed accuracy to within +/- 2 knots are also sufficient for AILS alerting. GPS using either a Local Area Augmentation System (LAAS) or a Wide Area Augmentation System (WAAS) will achieve the needed accuracies. 1 Hz GPS data updates are also adequate.

Since it is expected that AILS will have some reliance on broadcast Automatic Dependent Surveillance (ADS-B) using Extended Squitters to transmit GPS position reports via the Mode-S transponder, it is reasonable to assume that GPS will already be available for use by AILS.

7. Data Link Communication Requirements

To enable the AILS concept, a communication link is needed between intruder and evader aircraft to allow exchange and monitoring of core aircraft state data for the AILS alerting function. In addition, other procedural communications with ATC and between aircraft is needed.

Two options are available for AILS surveillance communications; 1) obtain needed aircraft state information of intruder aircraft via interrogations with subsequent replies, or 2) aircraft state information may be "squittered" by each aircraft to allow monitoring by other aircraft.

Since it is expected that the future National Airspace System (NAS) will utilize ADS-B surveillance in terminal and enroute areas for Air Traffic Management (ATM), and the likely ADS-B communications link for transmitting GPS position reports is Mode-S, this study has focused on the use of Mode-S as the AILS surveillance link.

Mode-S Specific Services have been defined by the SSR Improvements and Collision Avoidance Systems Panel (SICASP) Working Group 1 [8], that allow ATC ground stations to derive a substantial amount of aircraft state information via Mode-S Ground Initiated Comm-B (GICB) interrogations. The airborne Mode-S transponder maintains 255 GICB registers whose contents can be selectively requested via interrogations from ATC. A similar capability is being sought and defined by the SICASP Working Group 1 for an Airborne Collision Avoidance System (ACAS) Crosslink [9]. ACAS Crosslink allows an aircraft to obtain additional information from another aircraft via air-air interrogations and replies. This is one of the methods AILS could utilize to derive intruder aircraft state information.

Another mechanism currently being defined for air-to-air data exchanges over Mode-S is ADS-B Extended Squitter. Change NO. 2A of RTCA DO-181A [10] has defined a number of Extended Squitter formats that allow exchange of pertinent aircraft state data via squitters for airport surface, terminal area and enroute surveillance for ATM.

Thus conceptually, mechanisms are in place that can support either interrogation-based or squitter-based AILS data exchanges of AILS aircraft state information. However, not all state variables needed by AILS have been defined.

7.1 Current Extended Squitter Definitions

RTCA DO-181A, Change NO. 2A has defined the following Extended Squitter types:

1. Airborne position (GICB register 05H, transmitted 2 / sec with ± 0.1 sec jitter)
2. Surface position (GICB register 06H, transmitted 2 / sec with ± 0.1 sec jitter)
3. Aircraft ID (GICB register 08H, transmitted once per 5 sec with ± 0.2 sec jitter)
4. Airborne supplementary (GICB register 09H, transmitted 2 / sec with ± 0.1 sec jitter)
5. On-demand (GICB register 0AH, transmitted on occurrence of a specific event)

These squitters represent long replies of length 112 bits and are transmitted on downlink format (DF) = 17. The 112 bits consist of the standard 56 bit squitter in the All-Call reply format and is appended with an additional 56-bits to include the appropriate GICB register.

Change NO. 2A has defined protocols for selecting the squitter type to be transmitted, allows for squitter rate control, and also allows selection of the antenna to be used for transmitting the squitter. Squitter capability reports are used to inform ATC and other aircraft of an aircraft's capability to participate in Extended Squitter. Mechanisms are also in place to ensure the validity of Extended Squitter and GICB register data. Figure 7-1 illustrates the formats defined for airborne (GICB register 05H, also referred to as BDS 05H) and airborne supplementary (BDS 09H) squitters.

From Figure 7-1 it is evident that all of the core AILS state data except bank angle / roll is included in these squitter formats. The airborne position squitter provides 12 bits of altitude to 25 ft and 100 ft resolution, and provides latitude and longitude position to 5.1 meter accuracy using 17 bits that are encoded using Compact Position Reporting (CPR) [10]. The airborne supplementary squitter provides true track angle to 360/512 degree resolution and ground speed to 4 knots of resolution (Note: AILS alerting was successfully evaluated for +/- 2 knot ground speed accuracy; the 4 knot resolution requires additional simulations to determine if the provided resolution is sufficient for AILS alerting).

The airborne supplementary squitter has a sufficient number of spare bits to accommodate the additional bank angle information needed by the AILS alerting function. As the AILS concept matures, a request for incorporation of bank angle into the airborne supplementary may be warranted.

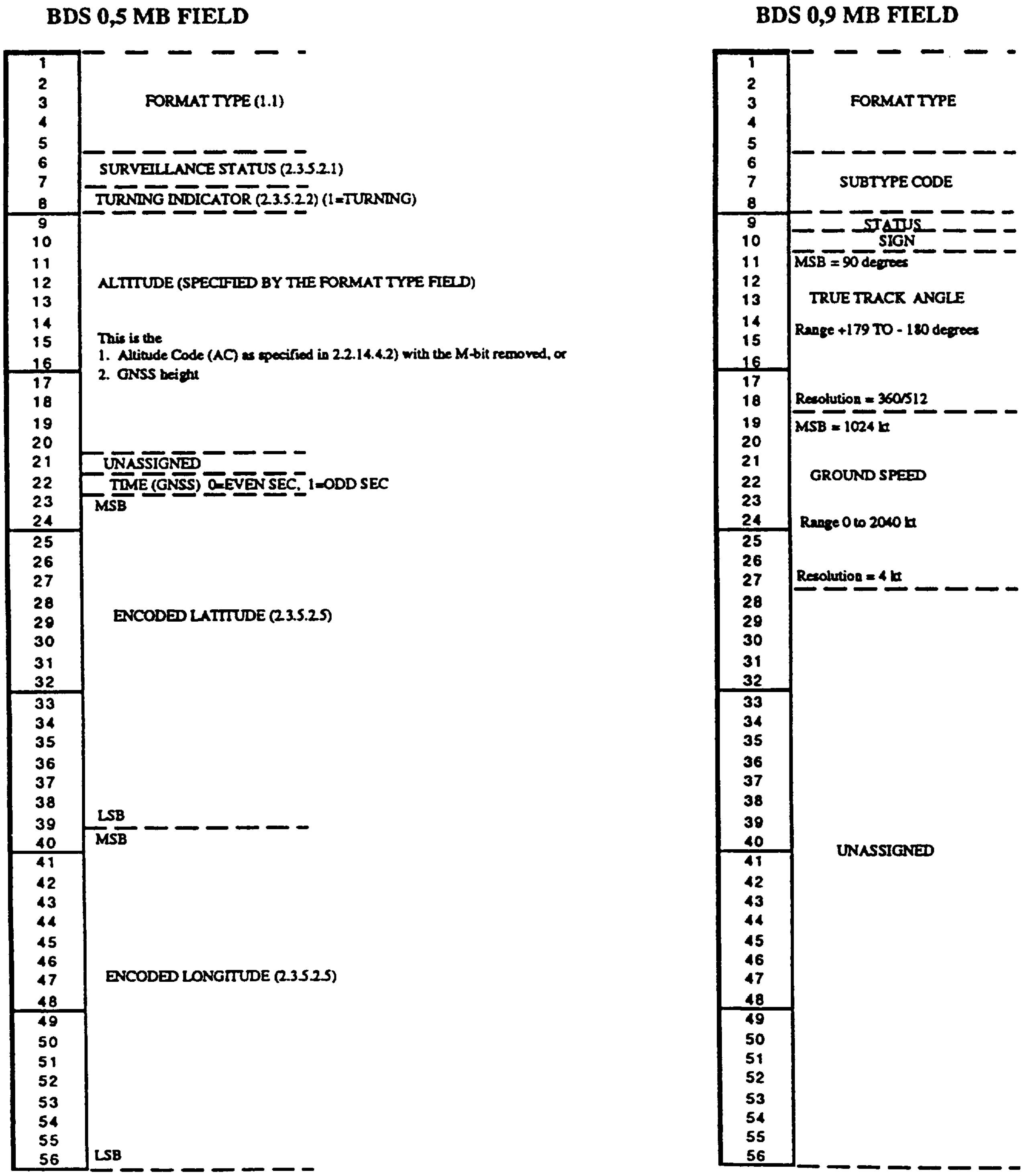
7.2 Current GICB Interrogation Formats for Possible ACAS Crosslink Use

Figure 7-2 shows two GICB formats defined as air-air state information #1 and #2, known as BDS 0BH and BDS 0CH, respectively. Again true track angle and ground speed are included in these register definitions. In addition, bank angle / roll is also included. Currently these GICB interrogations are intended for ATC requests for information but could easily be included on the ACAS Crosslink. From the definitions of these registers, it appears that these formats are in support of enroute operations where intent and next waypoint information is useful for ATM.

7.3 Impact of Link Failure Rate

As discussed in section 5.3.5, AILS alerting can support 1 Hz state data updates and withstand link failure rates of 10% to 20%. A closer look at link failure rate is warranted for an AILS/Mode-S based communications link using Extended Squitter.

Table 7-1 summarizes results of an analysis performed by MIT Lincoln Labs [11] that addresses the Extended Squitter reception probabilities by a TCAS or AILS receiver in the presence of airborne and surface squitter and reply fruit (interference) for a range of aircraft loadings and ADS-B equipage. Note that TCAS is the companion link for receiving Mode-S Extended Squitters. This same receiver could be used for reception of AILS-based Extended Squitters or replies to AILS ACAS Crosslink interrogations.



Airborne Squitter

Airborne Supplementary Squitter

Figure 7-1 Extended Squitter Formats

BDS 0,B MB field

1	STATUS
2	MSB = 1 024 Kt
3	
4	
5	
6	TRUE AIR SPEED
7	
8	
9	Range 0 to 2 047 Kt
10	
11	
12	Resolution = 1 .0 Kt
13	SWITCH
14	STATUS
15	SIGN
16	MSB = 90 degrees
17	
18	HEADING
19	
20	
21	Range +179 to - 180 degrees
22	
23	
24	Resolution = 360/1 024 degrees
25	STATUS
26	SIGN
27	MSB = 90 degrees
28	
29	
30	
31	
32	TRUE TRACK ANGLE
33	
34	
35	Range +179 to -180 degrees
36	
37	
38	
39	
40	Resolution = 360/32768degrees
41	MSB =1024 kt
42	
43	
44	
45	
46	GROUND SPEED
47	
48	
49	Range 0 to 2048 kt
50	
51	
52	
53	
54	
55	Resolution = 1/16 kt
56	UNASSIGNED

Air-Air State Information #1

BDS 0,C MB field

1	STATUS
2	MSB =65536ft
3	
4	
5	
6	LEVEL-OFF ALTITUDE
7	
8	
9	Range 0 to 131056 ft
10	
11	
12	
13	
14	Resolution = 16 ft
15	STATUS
16	SIGN
17	MSB = 90 degrees
18	
19	
20	NEXT COURSE (True Ground Track)
21	
22	Range + 179 to - 180 degrees
23	
24	
25	Resolution = 360/1 024 degrees
26	STATUS
27	MSB = 128 seconds
28	
29	TIME TO NEXT WAYPOINT
30	
31	
32	Range 0 to 255 seconds
33	
34	Resolution = 1.0 second
35	STATUS
36	SIGN
37	MSB 8192 feet per minute
38	
39	VERTICAL VELOCITY (Up is Positive)
40	
41	
42	Range +16 352 to -16 352 feet per minute
43	
44	
45	Resolution =32 feet per minute
46	STATUS
47	SIGN
48	MSB = 45 degrees
49	ROLL ANGLE
50	
51	Range +89 to - 89 degrees
52	
53	Resolution = 360/256 degrees
54	INTERCEPT BIT
55	UNASSIGNED
56	

Air-Air State Information #2

Figure 7-2 GICB Reply Formats

ADS Squitter Reception (per second) with Airborne and Surface Fruit

50% EQUIPAGE

	TCAS SQUITTER RECEPTION PROB (1 SEC) - AIRBORNE AND SURF FRUIT								
	CURRENT SHORT SQUITTER			GPS-SQUITTER			PROBABILITY DIFFERENCE		
AIRCRAFT	CASE 1	CASE 2	CASE 3	CASE 1	CASE 2	CASE 3	CASE 1	CASE 2	CASE 3
1	0.9792	0.9793	0.9793	0.9983	0.9983	0.9983	1.90%	1.90%	1.90%
10	0.9597	0.9630	0.9642	0.9948	0.9960	0.9964	3.52%	3.29%	3.22%
25	0.9144	0.9328	0.9396	0.9771	0.9883	0.9918	6.27%	5.56%	5.22%
50	0.8178	0.8758	0.9000	0.9002	0.9614	0.9807	8.24%	8.55%	8.07%
75	0.7108	0.8140	0.8621	0.7722	0.9146	0.9659	6.13%	10.06%	10.38%
100	0.6052	0.7503	0.8257	0.6225	0.8504	0.9479	1.73%	10.01%	12.22%

100% EQUIPAGE

	TCAS SQUITTER RECEPTION PROB (1 SEC) - AIRBORNE AND SURF FRUIT								
	CURRENT SHORT SQUITTER			GPS-SQUITTER			PROBABILITY DIFFERENCE		
AIRCRAFT	CASE 1	CASE 2	CASE 3	CASE 1	CASE 2	CASE 3	CASE 1	CASE 2	CASE 3
1	0.9792	0.9793	0.9793	0.9971	0.9972	0.9972	1.79%	1.79%	1.79%
10	0.9597	0.9630	0.9642	0.9933	0.9946	0.9951	3.36%	3.16%	3.09%
25	0.9144	0.9328	0.9396	0.9751	0.9868	0.9905	6.07%	5.40%	5.09%
50	0.8178	0.8758	0.9000	0.8990	0.9605	0.9800	8.12%	8.46%	8.00%
75	0.7108	0.8140	0.8621	0.7732	0.9155	0.9665	6.24%	10.14%	10.44%
100	0.6052	0.7503	0.8257	0.6258	0.8537	0.9504	2.07%	10.34%	12.47%

Table 7-1 Extended Squitter Reception Probabilities

Form "GPS-Squitter Interference Analysis" - MIT Lincoln Laboratory [11]

Table 7-1 provides reception probabilities for 1 second updates when 2 squitters are transmitted per second, thus two receive opportunities are available to achieve a 1 second update rate. From Table 7-1 it is evident that reception probabilities for Extended Squitters (referred to as GPS Squitter in the table) can be as low as 62 % for 100 aircraft located within 15 nmi of the TCAS/AILS receiver, 0% of which are equipped with ADS-B capability. Reception probability improves to ~95% when all aircraft are ADS-B equipped. While these reflect successful reception rates given two attempts per second, the single attempt reception probabilities fall as low as 39 % for 0% ADS-B equipage and improve to ~ 60% when 50% of aircraft are ADS-B equipped. Table 7-2 summarizes single attempt reception probabilities.

The 100 aircraft loading represents an extremely high traffic density, i.e., 100 aircraft are within 15 nmi of the TCAS/AILS aircraft receiver.

For 50 aircraft with 50 % ADS-B equipage the single attempt reception probability increases to 80 % resulting in an effective 1 second reception probability of 96 %. This reception probability is sufficient for AILS alerting. For full 100 aircraft traffic densities, an increase in the rate of AILS-based Extended Squitters exceeding the typical 2 / sec rate would ensure sufficient link reception rates. Note: Only a few aircraft, those performing AILS approaches, would be allowed to increase their squitter rate for the duration of the approach / landing flight phase.

First Attempt Probability of Reception		
Case 1	Case 2	Case 3
0.96	0.96	0.96
0.93	0.94	0.94
0.85	0.89	0.91
0.68	0.80	0.86
0.52	0.71	0.82
0.39	0.61	0.77

Case 1- 0% ADS-B equipage
Case 2 - 50% ADS-B equipage
Case 3 - 100% ADS-B equipage

Table 7-2 First Attempt Reception Probabilities of an Extended Squitter

7.4 Potential Need for Time Tagging of AILS Position Updates

Due to the close spacings and the high approach speeds it appears that time tagging of GPS position updates may be required. At present, ADS-B position reports are envisioned as follows: 1) The GPS sensor provides a position update at a 1 Hz rate; 2) the new position report is written into the appropriate Mode-S GICB register (BDS 05H); 3) the Mode-S transponder generates a squitter of this data at a 2 per second rate using a time jitter of +/- 0.1 sec. Due to the asynchronous nature of the GPS sensor position update and the actual transmission of the ADS-B squitter, a time uncertainty of as much as 0.5 seconds is possible. During this time, an aircraft traveling at 270 ft/sec during the runway approach phase experiences an along track position error as large as 135 ft. While this has not been simulated, it is expected that such a large along track position uncertainty would degrade AILS alerting performance to the 500 ft protection volume.

Possible options to reduce this position uncertainty are: 1) several bits of GPS time tag information are also squittered to allow the receiving aircraft to determine the time difference between the GPS sensor update time and the actual time of squitter reception; 2) the transmitting aircraft, just prior to transmitting the position squitter, updates the position report to account for the time elapsed since the GPS sensor output; 3) an increase in squitter rate to perhaps as high as 10 / sec to reduce the position uncertainty to 27 ft.

Option 1 requires that both aircraft are locked to GPS time and that several additional bits (3 or 4) of time tag data are set aside in the Extended Squitter. At present, these squitters are fully defined and have no additional spare bits for time tagging.

Option 2 requires additional processing by the Mode-S transponder not currently defined in order to compute an updated position report at the time of squitter transmission. The update is based on the elapsed time since the GPS sensor output was provided.

Option 3 would allow a reduction in position uncertainty and at the same time boost the reception probability by allowing more opportunities to receive position reports. This could easily be incorporated as an AILS Extended Squitter mode that can be controlled by ATC. Additional loading on the Mode-S link can be mitigated by only allowing the relatively small number of aircraft executing an AILS parallel approach operation to use the higher squitter rates (likely under ATC rate control).

7.5 Other AILS Data Link Communications

Other probable AILS data to be data linked are:

1. Aircraft ID.
2. Runway ID indicating the runway used for approach and landing. This allows both aircraft on an AILS approach to cross check each others landing intent to avoid inadvertent landings on the same run.
3. Location of installed antennas (GPS, upper and lower Mode-S antennas).
   Location data indicates X, Z position relative to nose of aircraft. This allows for adjustment to position information; GPS antenna location may be used to refine ADS-B position reports; Mode-S antenna location may be used to refine TCAS range and ground multilateration surveillance range.
4. TSE (total system error) containment status of other aircraft; i.e., does other aircraft think it is meeting it's allocated Required Navigation Performance (RNP) for the AILS approach. Conversely, own aircraft monitors it's own TSE containment and sets it's TSE containment status field. This information could be included in a "squitter" or could be provided via request from the other aircraft.
5. DGPS related data.
   DGPS corrections and approach waypoints.

Note: CPROPS will require a number of procedural communications between ATC and also with the adjoining parallel traffic. Procedural exchanges between ATC and adjoining aircraft can be accomplished via Controller Pilot Data Link Communications (CPDLC) or using the ACAS Crosslink.

AILS CPDLC is tactical in nature and will require low-latency communications. Presently, Mode-S is the only viable tactical link capable of fast updates. Whether Mode-S is the appropriate tactical CPDLC link is to be determined and is outside the scope of this study. If Mode-S is used for these tactical AILS-based CPDLC communications, the latency of a rotating Secondary Surveillance Radar (SSR) sensor may be excessive (4.8 sec), and it may become necessary to equip the ground with an omni or sectored, low-latency CPDLC Mode-S ground station.

Procedural communications may consist of the following notifications:

1) TSE containment warnings.
2) Go-around instructions or intent to perform a go-around.
3) Evasive maneuver instructions or intent to perform an evasive maneuver.
4) Cross check of proper runway ID.
5) Instructions from ATC to commence transmission of AILS Extended Squitters.

8. Required Airspace Infrastructure for AILS

Since AILS is essentially a flight-deck centered system, only limited airspace infrastructure is needed to support AILS. The major sub-systems of AILS are the Parallel Runway RNP sub-system used for conformance monitoring of own aircraft during the approach and landing flight phases, and the AILS Alerting sub-system which serves as a back-up system in the event of a blunder by the intruder during independent parallel runway approaches.

Infrastructure requirements are primarily for augmentation support of the GPS/GNSS navigation system, surveillance, and data link. In addition, the ground controller may require a situational awareness display that emulates the AILS alerting function on the ground.

The GPS navigation system may be augmented by a Local Area Augmentation System (LAAS) or a Wide Area Augmentation System (WAAS). Both augmentations will suffice for AILS in terms of achievable accuracy. A typical LAAS system will require a ground reference GPS/GNSS receiver, DGNSS data processing, a DGNSS signal integrity monitor function, and a DGNSS uplink broadcast transmitter for sending correction data and waypoints. The data link for DGNSS is still being debated in industry. A VHF Time Division Multiple Access (TDMA) broadcast transmitter using navigation frequencies (108-118 MHz is being considered as a likely candidate (RTCA DO-217, Appendix F).

If WAAS is used, the ground-based infrastructure will require development of a continental system consisting of ~24 reference stations, 2 control stations and 3 INMARSAT GEO satellites. WAAS correction and integrity data is uplinked to the INMARSAT satellites, which then broadcast this data via the WAAS GPS signal.

Even though AILS provides airborne alerting / separation assurance against parallel runway approach blunders, a ground surveillance system will be required to allow ATC to provide ATM and separation assurance. The ground surveillance system will likely utilize the current SSR system and will begin to transition to more global implementation of ADS-B. Instead of using rotating beam SSRs, use of omni and sectored ground stations is being considered in support of ADS-B surveillance.

AILS may use a data link to ATC for procedural communications. These communications will tend to be tactical in nature for the flight phases encompassed by AILS. At present Mode-S is the only viable data link for "tactical" Controller Pilot Data Link Communications (CPDLC).

In order to provide the ground controller with improved situational awareness, it may be appropriate to provide an AILS monitor and display to emulate the airborne AILS alerting system. However, the primary separation assurance system is expected to be in the AILS avionics system in the aircraft.

AILS will need to coexist with the planned ADS-B Extended Squitter surveillance system and will likely utilize the Mode-S channel (1030/1090 MHz). MIT Lincoln Laboratories has analyzed the capacity and interference of a Mode-S based ADS-B system [11][12]. Conclusions suggest that Extended Squitter can be accommodated without appreciable interference effects on current system operation on the Mode-S frequencies, while supporting a high-density air traffic environment. AILS using Mode-S is not expected to adversely affect Mode-S ADS-B environment.

9. Assessment of Avionics for AILS

The following capabilities are required for an AILS system:

1. Avionics for "conformance monitoring" of own approach path, i.e., Required Navigation Performance (RNP) to a predefined parallel runway approach path / tunnel.
2. ADS-B / surveillance data link.
3. AILS alerting avionics.
4. Aircraft Sensors.
5. Aircraft Displays.

9.1 AILS RNP Avionics

While the primary focus of this study has been on the development of alerting algorithms to warn against approach blunders by the intruder aircraft, an important component of AILS is conformance monitoring of "own" aircraft's performance and adherence to its approach path. This "self" conformance monitoring is also termed Required Navigation Performance (RNP). Figure 9-1 illustrates NASA' preliminary concept of AILS RNP for parallel runway approaches. The AILS RNP "Rocket Ship" shown in Figure 9-1 defines a lateral approach tunnel to which each aircraft is expected to adhere. In addition to the lateral "Rocket Ship" tunnel, RNP attitude, consisting of own aircraft's track heading and bank angle, is monitored to detect RNP containment and attitude violations by own aircraft. Note: RTCA SC-181 is currently defining Minimum Aviation System Performance Standards for a range of RNP capabilities. NASA's "Rocket Ship" is an example of one such RNP tunnel concept.

In order for an aircraft to meet its parallel approach RNP, navigation and flight technical errors must be monitored to a high-level of integrity. Future parallel runway approaches will likely use a combination of ILS, MLS and GPS for navigation, also called the Multi-Mode Receiver (MMR). A navigation processor will be needed to blend the appropriate mix of navigation signals that may be available into a single guidance signal. This navigation processor will also measure the Flight Technical Error (FTE) in order to determine if RNP containment to the parallel runway approach tunnel or path is being met, i.e., it is the navigation processor that detects Total System Error (TSE) containment violations. Navigation processing could be implemented within the MMR.

A navigation database is likely required to allow comparison of the actual flight path to the reference flight path in order to determine FTE and allow monitoring of RNP performance. The database may be stored on the aircraft or could be provided via data link, e.g., DGPS uplink of correction data and approach waypoints. An on-board database could reside within the MMR.

An augmented GPS/GNSS receiver will probably be required for AILS RNP and AILS intruder alerting. For LAAS, an airborne data link receiver is required for receiving DGPS correction data and also possibly for approach waypoints. The industry has not yet down selected the type of data link needed for this application. A VHF broadcast TDMA radio as defined in the Special CAT-1 Approach System MASPS, DO-217 Appendix F is a likely candidate. If WAAS is used, the need for an additional data link for GPS corrections data is eliminated; corrections are received via a WAAS capable GPS receiver. An augmented GPS system is already expected to be required for ADS-B, thus AILS can take advantage of existing equipment.

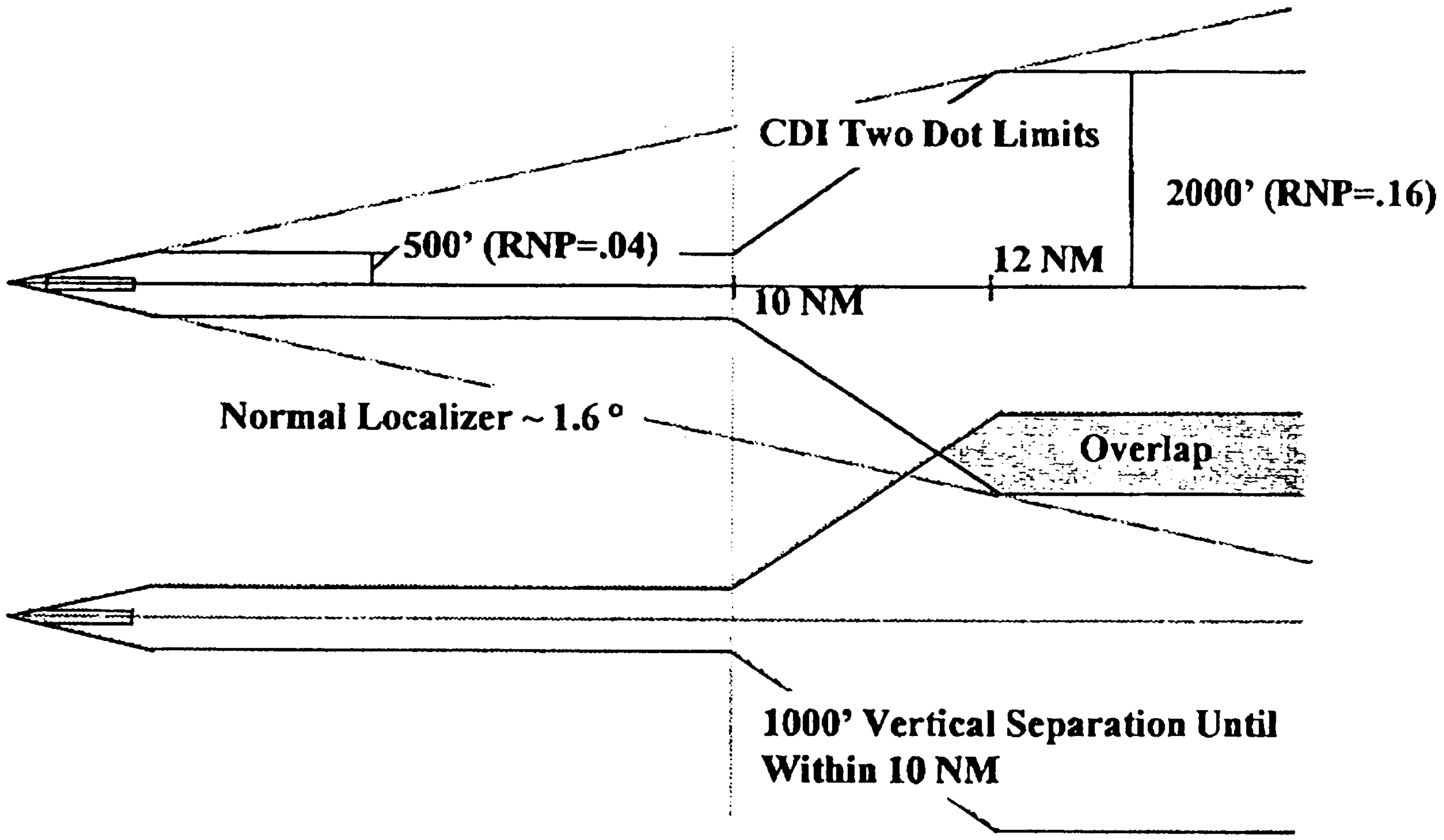


Figure 9-1 AILS Required Navigation Performance (RNP) "Rocket Ship"

9.2 ADS-B / Surveillance Data Link

The current definition of Extended Squitter (DO-181A, Change NO. 2A, [10]) nearly provides the needed surveillance capability for AILS. Bank angle information is still required and there is the issue of time tagging position reports (section 7.4). AILS surveillance and alerting is compatible with the planned ADS-B surveillance system.

Upgraded Mode-S and TCAS receiver-transmitter avionics are needed to provide the surveillance capability for the AILS alerting sub-system.

While not a requirement, some AILS procedural communications between an aircraft and ATC or air-to-air communications may be desirable. Such communications would likely require a tactical data link. At present, the Mode-S link is the only available link capable of tactical, low-latency communications. Other data links may be considered as the AILS concept matures.

9.3 AILS Alerting Avionics

AILS is very similar to TCAS as an alerting system. In fact, AILS can be considered as a specific mode of TCAS for providing separation assurance during parallel runway approach operations. While Mode-S and TCAS receiver-transmitters upgraded to AILS capability provide surveillance data, an AILS "TCAS" like processing system is needed. Ultimately, AILS alerting would consist of additional software within TCAS that is enabled during parallel runway approaches.

9.4 Avionics Sensors

An IRS is needed to provide bank angle / roll information for AILS alerting. The remaining AILS core state data is provided by the augmented GPS system, i.e., latitudinal and longitudinal position, true track angle/heading, and ground speed.

9.5 Displays

NASA has developed prototype display formats and symbology that provide the flight crew with AILS situational awareness and some guidance cues. These will be provided via the Primary Flight Display (PFD) and Navigation Display (ND). Display generators capable of data loading allow for rapid prototyping of AILS display concepts.

10. Existing and Evolving PRM Techniques

This section discusses existing and evolving techniques and systems that have the potential to permit operations during instrument meteorological conditions (IMC) on parallel runways with a separation of less than 4,300 feet.

There is only one system and it is still under development that will permit independent aircraft operations during IMC when the runway spacing is less than 4,300 feet. That system is the Precision Runway Monitor (PRM) system being developed and tested by the FAA. The PRM is based on a high update rate (1 to 2 updates per second) radar to determine aircraft position. Several enhancements have also been proposed for this system. One enhancement is to augment or replace the radar position information with GPS-based position broadcast from the participating aircraft. Another enhancement would be to replace the radar derived position information with position information derived from a multilateration system. Multilateration, based on radio triangulation techniques, is one of the techniques being investigated to provide position information for the Airport Surface Traffic Automation (ASTA) system.

The PRM and the enhanced PRM systems are discussed in the following sections. A high level cost discussion follows the system descriptions.

10.1 FAA Precision Runway Monitor

The FAA Precision Runway Monitor system is described in [3]. The PRM demonstrations produced a broad recognition that the system could be used at the 3,400 foot runway spacings.

Five limited production radar systems with the electronically-scanned antennas have been ordered and/or delivered. The first one is being (or will soon will be) installed at Minneapolis (MSP). Other airports under consideration are JFK, Philadelphia, Atlanta, and Pittsburgh. St. Louis is also being considered for a PRM installation and a cost benefits analysis is being conducted by the FAA.

The FAA Technical Center has determined that the PRM will not work when the runway spacing is 3,000 foot or less. The failure was caused by the nominal communication lags in contacting the pilot after the controller determines there is a threat. The communication lag is too great even without considering the blocked message problem.

Along with the PRM, the FAA is developing a Final Monitor Aid (FMA). The FMA provides a display to assist controllers with the task of monitoring aircraft spacings during approaches to closely-spaced parallel runways. The FMA can also be used with the augmented PRM systems discussed in the following sections.

10.2 PRM Augmented with GPS

The FAA's Aviation System Capital Investment Plan - June 1995 [6] reports that the FAA plans to investigate the combined use of PRM with GPS. The Automatic Dependent Surveillance-Broadcast (ADS-B) system has been proposed for position tracking of aircraft. In domestic terminal area airspace, the airborne ADS-B system is capable of broadcasting current GPS position two times per second. If ADS-B comes into widespread use by airlines, a ground-based receiver could receive aircraft position reports and the PRM system could use that information in place of the electronically-scanned radar derived position information.

The airlines will probably not be able to cost justify the installation of ADS-B only for PRM. However, if ADS-B is installed for other purposes it could also be used for PRM.

The use of more accurate navigation/landing systems such as GPS will reduce random path tracking errors and thus make it easier to determine real blunders. This may allow PRM to be used for runway spacings of less than 3,000 feet. The improved blunder detection capability made possible by the reduced random path tracking errors will benefit all the systems discussed here, including AILS so this benefit is not unique to the PRM.

10.3 PRM Augmented with Multilateration

The use of multilateration position determination could replace the electronically-scanned antenna used by the current PRM implementation.

Multilateration is one of the techniques being investigated to provide position information for the Airport Surface Traffic Automation (ASTA) surveillance system. Multilateration is based on a radio triangulation technique. Multiple ground stations receive a radio signal from the aircraft and position is determined by the difference in time of arrival of the signal at the different ground stations. The radio signal used by the multilateration system is the signal from the existing Mode S transponders on commercial aircraft. Thus, no extra equipment needs to be installed on the aircraft for the multilateration system, whereas the GPS augmentation discussed in the previous section will require that ADS-B or a similar system be installed on the aircraft.

Multilateration will only be practical for PRM if it is implemented for ASTA. Depending on airport size and layout, the ASTA surveillance system will require 5-10 (or more) ground stations and a central processor for multilateration. Multilateration for use with PRM will require that an additional 3-5 ground stations be added to the ASTA system. The additional ground stations would need to be located outside the periphery of the airport boundaries in order to give a geometry suitable for position determination during approach. Locations off the airport would have to be secure sites to prevent tampering with the navigation aid.

10.4 PRM Cost Considerations

This section compares the relative cost of the systems discussed above. Except as noted the cost information (in 1991 dollars) in this section is taken from RTCA/DO-211 report Appendix C [7].

The PRM-Multilateration system cost with ASTA-Multilateration already installed at the airport is based on the assumption that 5 additional ground stations are required and that the cost of each station is equivalent to one Ground Based ADS-B station ($200,000).

The ground based system costs are average installed costs but do not include buildings and land. It is assumed that GPS/GNSS receivers are already installed on the aircraft. The system capital costs are show in Table 10-1.

As stated in the PRM Report, there are ten major airports in the USA with runway spacings between 3,000 feet and 4,300 feet. These airports are:

Ft. Lauderdale
Salt Lake City
Detroit
Phoenix
Raleigh-Durham
Memphis
Minneapolis-St. Paul
Portland
JFK
Dallas Love

Table 10-2 shows the capital costs to implement the various systems at 10 airports.

Note: A multilateration analysis tool developed for another study was used to assess achievable accuracies of a PRM system based on multilateration using aircraft transponder transmissions. These results are described in Appendix D.

Table 10-1 Estimated Capital Equipment Costs

System	Ground Systems Required			Airborne Systems	
	Controller display system	Mode-S with E-Scanned Antenna	Ground Based ADS-B	Equipment that is assumed to be installed on the aircraft.	Display and System processing required.
PRM	yes	$2,000,000		Mode S	no
PRM/ADS-B	yes		$200,000	ADS-B	no
PRM-Multilateration ASTA-Multilateration not installed	yes	$2,000,000		Mode S	no
PRM-Multilateration ASTA-Multilateration installed	yes	$1,000,000		Mode S	no
AILS	maybe		$200,000	Mode S or enhanced ADS-B	yes

Table 10-2 Estimated Total System Capital Costs

System	Ground System Cost - Based on 10 airports with parallel runway spacings between 3000 and 4300 feet.	Airborne System Cost
PRM	$20,000,000	
PRM/ADS-B	$2,000,000	
PRM-Multilateration ASTA-Multilateration not installed	$20,000,000	
PRM-Multilateration ASTA-Multilateration installed	$10,000,000	
AILS	$2,000,000	Display and Display Processing

11. Summary and Future Plans

This report has described the development of a prototype Airborne Information for Lateral Spacing (AILS) system. AILS is envisioned as a flight-deck centered parallel runway approach system to allow simultaneous, independent parallel approaches to closely-spaced runways in low-visibility conditions. NASA Ames and NASA Langley Research Centers are the sponsors of this program that falls under a larger program that address Terminal Area Productivity (TAP).

While this report alludes to the overall AILS concept and describes the activities and roles of the NASA AILS team, the primary purpose of this report is to document Rockwell Collins Avionics' study of a prototype AILS alerting system.

A simulation program was developed to allow Monte Carlo evaluation of candidate AILS alerting algorithms to determine the extent of runway spacings that may be supported. Flight track templates/scenarios were flown on a Fokker 70 part-task simulator to generate realistic aircraft state representations of normal, blunder, fake blunder, and evasive maneuver tracks.

A number of factors influence the performance of the AILS alerting system; 1) cross-track offset (i.e., Flight Technical Error, FTE), 2) longitudinal-track offset, 3) pilot and aircraft response time, 4) type of evasive maneuver used, 5) effect of avionics sensor uncertainty on state data, 6) data update rate, and 7) data link failure rate.

Based on simulations and using conservative probability distributions to represent pilot / aircraft response time it appears that a 2,500 ft runway spacing is viable for proper alerting performance in terms of probability of missed detection and probability of false alarms when detecting for aircraft blunders. Pilot response time is the primary factor affecting AILS alerting and the achievable runway spacing. With proper training and appropriate situational awareness, pilot response times may be reduced considerably below those referred to above. This may allow for a further reduction of runway spacings perhaps as low as 1,700 ft.

To obtain an indication of pilot response time using the AILS alerting system described in this report, NASA Langley is conducting flight simulator evaluation using subject pilots to gather data on pilot response time and workload while performing an AILS-type approach. PFD and ND displays provide situational awareness and guidance cues for pilots in these experiments. These results will be folded back into the Monte Carlo Simulation to further assess AILS alerting system performance.

In addition to developing a prototype AILS alerting system, this study also addressed AILS avionics and infrastructure requirements. Being a flight-deck centered system, AILS requires a minimum of infrastructure support. Infrastructure support consists primarily of GPS/GNSS, ADS-B and CPDLC data link and perhaps a ground controller AILS situational awareness display.

Avionics requirements are also relatively minimal since AILS can be viewed as a new, additional mode of TCAS and can use existing and future versions of Mode-S and TCAS receiver-transmitter avionics for surveillance and air-to-air communications using ACAS Crosslink. AILS alerting is a software task that could be incorporated with TCAS. In addition to surveillance and alerting functions, AILS also requires conformance monitoring of own aircraft on its approach flight path. The AILS RNP sub-system provides this capability. This task did not focus on the development of an AILS RNP sub-system.

Controller Pilot Data Link Communications (CPDLC) for AILS are primarily tactical in nature. The future data link for AILS CPDLC procedural communications is yet to be determined by industry, although Mode-S is currently the only viable link that is available.

Future plans for the NASA AILS team are to continue to evolve the AILS concept. In the near term, NASA Langley is conducting flight simulator evaluation of the initial AILS alerting system and display concepts using subject pilots to determine pilot response time and workload. This data will be folded back into Monte Carlo simulations of AILS alerting to reassess AILS alerting performance for a large number of aircraft blunders.

NASA Langley and NASA Ames will continue to evolve AILS display formats and symbology to provide the flight crew with situational awareness and guidance during AILS approaches.

While the primary focus has been on the AILS alerting system, the NASA AILS team plans to put more emphasis on the development of the AILS RNP sub-system for conformance monitoring of own aircraft during the approach phase. NASA is planning to perform flight tests of both AILS RNP and AILS alerting sub-system concepts in 1997.

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Appendix A

AILS Guidelines and Procedures

Table A-1
Guidelines for Airborne Information for Lateral Spacing (AILS)
(Draft #2 9/15/95)

This Appendix documents guidelines for the development of AILS. It represents preliminary thoughts and guidelines developed by the NASA team. It is expected that this document will be updated as warranted as the AILS concept continues to evolve.

I. Purpose & Scope:

A. This document presents the guidelines for the development of controls, displays, alerts, warnings, and procedures for airborne systems that ensure adequate aircraft separation during closely-spaced parallel runway operations, i.e., Airborne Information for Lateral Spacing (AILS).

B. AILS shall consider: (1) airborne devices in the intruding aircraft that reduce both the probability that it will deviate from its assigned airspace and the magnitude of any such deviation;(2) airborne devices in the evading aircraft that will prevent separations of less than 500 feet, and (3) ground devices that may be needed by ATC to control closely-spaced parallel approach traffic prior to the approach, during the approach, and after the initiation of the evasion maneuver.

C. The AILS system development shall include recommended changes to ATC and flight crew procedures and training.

II. Definitions:

A. ATC - The appropriate part of the Air Traffic Control system that is responsible for separation of aircraft immediately before, during and immediately after closely-spaced parallel runway operations.

B. Intruding Aircraft - an aircraft that has deviated from its assigned airspace and may cause a potential collision with another aircraft.

C. Evading Aircraft - an aircraft that is within its assigned airspace but may have to maneuver to avoid an intruding aircraft.

D. Caution - Visual and aural alert of a time sensitive situation.

E. Warning - Visual and aural alert of a time critical situation.

III. Human Factors Considerations:

A. Any additional pilot requirement(s) during the approach and landing phases of flight shall be reasonable and necessary.

B. Any information that is added to the cockpit displays to satisfy an additional pilot requirement shall be necessary and sufficient to satisfy the requirement.

C. Because of the high workload associated with the approach and landing phases of flight, AILS tasks and displays shall not distract the pilot from his primary duties of controlling the flight path.

D. Any airborne display that shows the position of the intruding and evading aircraft shall accurately present all relevant and required information about both aircraft.

E. The AILS alert and avoidance maneuver generation system shall use the standard FAA pilot reaction time of 2 seconds.

F. The AILS alert and avoidance maneuver generation system must be reliable to the pilots of both aircraft by detecting any maneuvers that jeopardize 500 foot minimum separation and generating appropriate alerts for each aircraft with a minimum of false alarms.

G. The appropriate roles of the pilot and of the AILS system in deciding and acting upon alerts and avoidance maneuvers shall be determined.

IV. Cautions and Warnings:

A. Neither cautions nor warnings shall be given to the crew of the intruding aircraft as long as the aircraft is forecast to remain in its assigned airspace (Definition of assigned airspace is TBD).

B. Warnings in the intruding aircraft shall be given when the aircraft has deviated from its assigned airspace.

C. Neither cautions nor warnings shall be given to the crew of the evading aircraft unless there is a threat to the evading aircraft.

D. Warnings in the evading aircraft shall be given when evasive action is required to maintain at least 500 feet separation.

E. Alerts and warnings for the evading aircraft shall activate with sufficient lead time to allow for safe execution (at least 500 feet separation) of the avoidance maneuver.

F. Once a warning has been given to the evading aircraft, the approach shall be considered abandoned.

G. If separation of less than 500 feet is possible during the evasion maneuver, display information shall be provided to the pilot.

V. Operational Considerations:

A. In consideration of existing TCAS technology, AILS displays should be as lose to TCAS displays as possible. AILS displays must be operationally compatible with TCAS.

B. The AILS controls, displays, alerts, and warnings should consider the appropriate SAE Aerospace Standards (AS), Aerospace Recommended Practices (ARP), and Aerospace Information Reports (AIR). Any deviations should be documented.

C. Evasive strategies should consider the various parameters needed to optimize the separation distance such as: (1) optimum time to initiate the evading maneuver, (2) optimum bank angle during the evading maneuver, (3) optimum direction of turn, or flight path angle, (4) optimum duration of the maneuver, (5) optimum vertical maneuver strength, and (6) terrain clearance.

D. Evasive strategies should consider dynamic conditions when both aircraft are maneuvering as well as static conditions when only the evading aircraft is maneuvering. *(The intent of this paragraph is to consider the dynamic case when the intruder begins an intrusion, causing the evader to start the evasion maneuver, and then the intruder recognizes his error and reverses direction back towards his runway).*

E. To be operationally realistic, scenarios should include, but are not limited to, typical operational human errors such as: (1) tuning the wrong ILS frequency or missed approach navigation aid, (2) visual maneuvering to the wrong runway, (3) incorrect or misunderstood clearances, (4) tracking errors resulting from strong cross winds, (5) failure to recognize malfunctioning equipment, (6) overshoots during localizer intercept, and (7) simultaneous go-arounds.

F. To be operationally representative, intruding scenarios should represent all possible collision and near-miss trajectories, with different rates of lateral and vertical convergence of the intruding aircraft, and with different relative speeds between the aircraft.

G. The closely-spaced parallel approach system shall be validated in manual, and automatic (Flight Director and Autopilot) control modes under various crosswind and turbulence levels.

H. Special approach charts, cockpit procedures, and checklists shall be developed for the pilot flying and for the pilot not-flying .

I. ATC procedures shall be developed for closely-spaced parallel approaches.

J. If necessary, operational constraints such as along-track stagger, airspeed, weather, airborne equipment, runway geometry, ground equipment, NAVAIDS, and ATC may be used in the development of an AILS system.

Table A-2
Procedures and Assumptions for Initial Flight Simulation Alerting Experiments

Operational Information and Assumptions:

1. Initial flight simulation will be based upon a Glass Cockpit flight deck environment.
2. Approaches will be flown into parallel runways 26L and 26R at Denver International Airport, Colorado with a simulated spacing of 3400'.
3. Light to moderate turbulence will be implemented for all approaches.
4. All approaches will be flown manually.
5. Flight Director (FD) guidance will be available for the instrument approach but will not provide maneuver guidance for the avoidance of an intruder.
6. The simulation will provide auto-throttle speed control.
7. Reference speed for final approach will be TBD knots indicated airspeed (KIAS).
8. ATC will not respond to any communications relating to converging traffic. Pilot Flying (PF) must fly, decide and avoid based on AILS alerts.
9. Pilot Not Flying (PNF) will **NOT** provide any assistance during converging traffic alerts, conflict resolution decision making or evasive maneuvering.
10. PF can ask the PNF for clarification of other general issues not involved in the actual conflict resolution.
11. PF can and should request PNF to make necessary ATC contacts.

Closely Spaced Parallel Approach Simulation:

12. Approach plates will be provided indicating the Missed Approach (MA) procedure necessary to accommodate the intended breakoff maneuver.
13. Scenarios will start with the aircraft on a heading (HDG) to intercept the Localizer (LOC).
14. Expect to intercept the LOC at least 2 NM outside Final Approach Fix (FAF).
15. PF should call for appropriate items to configure Aircraft (A/C) for landing prior to FAF.
16. PF should intercept and fly the Glide Slope (G/S).

17. The actual encounter with intruding traffic will be dispersed along the final approach path between the FAF and the Runway (RWY).

18. PF shall be expected to detect and maneuver appropriately away from the intruding aircraft by utilizing up to a 30° bank and 2,000 Foot Per Minute (FPM) climb. The turn shall be according to the evasive maneuver heading cue presented on the navigation display compass rose, which is 45 degrees from runway heading away from intruder.

19. When the PF determines that the conflict has been appropriately resolved, the aircraft should be turned back to the RWY HDG and ATC should be contacted.

Alerting Information:

1. A Level 2 Caution Alert (yellow) indicates that traffic is converging.

2. For this evaluation, a Level 2 Caution alert will indicate that a level 3 Warning may follow and is intended as a precursor to prepare the PF for an avoidance maneuver.

3. A Level 3 Warning Alert (Red) indicates that converging traffic has become a hazard and an avoidance maneuver is required.

4. When a Level 3 Warning Alert is received the PF must break off the approach, reconfigure for a missed approach, start a climbing turn away from the intruder.

Maneuvering Information:

1. Successful maneuver requires an A/C reconfiguration for a missed approach Type climb. Turn away from intruder using a 45 degree heading turn and using a 2,000 FPM climb.

Appendix B

Total System Error Analysis

Appendix B Total System Error Analysis

This section provides results of an analysis of Total System Error (TSE) for runway approaches using ILS and GPS navigation systems. Manual and autopilot approaches are considered.

The Total System Error (TSE) is the total error between the desired flight path and the actual flight path. TSE is comprised of navigation system and flight technical errors. The Navigation System Error (NSE) is the difference between the true aircraft position and the sensed or measured aircraft position. The Flight Technical Error (FTE) is the error associated with controlling the aircraft flight path to null the deviation (or error signal) as determined by the navigation system.

Assuming that the NSE and FTE errors are independent and normally distributed, the standard deviation of the TSE is related to the NSE and FTE as:

$$\mathrm{TSE} = (\mathrm{NSE}^2 + \mathrm{FTE}^2)^{0.5}.$$

In order to estimate the total system error, the task is broken down in the subtasks of estimating the NSE and FTE.

Navigation System Error (NSE)

The NSE for ILS- and GPS-based aircraft navigation systems was estimated based on the error characteristics of each. The ILS system sources that contribute to the NSE include the ILS beam alignment, the ILS beam bends, and the airborne ILS receiver. These errors associated with a Type I, Type II, and Type III ILS beams for 9000' and 12,000' runways have been estimated based on the minimum requirements of such systems as specified in RTCA and ICAO documents (references are given below) The table in Attachment #2 summarizes the ILS localizer beam error specifications. The performance of fielded ILS systems may be better than the specified minimum requirements.

The performance of non-augmented GPS has been "guaranteed" to be less than 100 meters (328 feet) horizontally [95%] by the DOD GPS Standard Positioning Service (SPS). If GPS is augmented, e.g., with the Wide Area Augmentation System (WAAS) or a Local Area Augmentation System (LAAS), the associated navigation errors will be greatly reduced. In order to support precision approach operations, the accuracy of such systems is being specified by the FAA precision approach tunnel as well as in FAA WAAS and LAAS documents.

References:

1. ICAO Annex 10, Aeronautical Telecommunications, Volume I (4th Edition), April 1985.
2. RTCA/DO-117 -- Standard Adjustment Criteria for Airborne Localizer and Glide Slope Receivers, March 14, 1963.
3. FAA Local Area Augmentation System (LAAS) Request for Proposal, February 17, 1995.

4. FAA Specification for the Wide Area Augmentation System (WAAS)
5. Required Navigation Performance (RNP) for Precision Approach and Landing with GNSS Application, by R.J. Kelly, and J.M. Davis, *Journal of the Institute of Navigation*, Vol. 41, No. 1, Spring 1994.

Flight Technical Error (FTE)

Flight Technical Error (FTE) includes the errors associated with controlling the aircraft to the desired location as determined by the navigation system. This error may include the autopilot or the pilot (and the displays) as well as all the other sensor information used in the aircraft control algorithms. At this point, we have not conducted extensive research into the true size of the FTE error. However, as a preliminary estimate, if the pilot is manually flying the aircraft, it is believed that he can easily keep the aircraft within 0.5 to 1.0 dot [95%] on the Course Deviation Indicator (CDI) after he has stabilized the aircraft on the approach flight path.

As a preliminary estimate, it is believed that an autopilot can maintain the aircraft to within 100 feet [95%] of the desired position over the range of 5 to 15 nautical miles from the airport. As the autopilot gets closer to the runway, the gains in the control loops are typically increased to maintain tighter tracking to the desired flight path. However, father out, the gains are more relaxed to allow for less control motion input. Once again, this is just a rough estimate since the FTE is a function of the conditions (e.g., wind gusts), aircraft responsiveness, autopilot control algorithms, and the avionics sensor suite used to provide inputs to the autopilot.

Quantitative Analysis

A preliminary quantitative analysis was conducted to estimate the TSE at 5, 10, and 15 nautical miles from the runway threshold. The tabulation of this analysis appears in Attachment #1. ILS and GPS navigation landing aids are considered. For both navigation systems, the use of a conventional CDI display is assumed for manual approaches. This attachment provides an estimate of the horizontal errors based on the minimum system requirements associated with conducting an ILS approach to both 9000' and 12,000' runways using Type I, Type II, and Type III ILS beams (refer to Tables 1 and 2). The worst case ILS navigation system errors are on the shorter runway with the Type I (poorest quality) ILS beam. The worst case FTE errors for the manually flown aircraft also appear on the shorter runway because of the reduced sensitivity of the CDI on the shorter runway. Manually flown parallel runway approaches may wish to have the capability to increase the sensitivity of the flight director display (e.g., CDI) to reduce FTE.

The horizontal system error specifications for the GPS-based approach system are also given in Attachment #1. The navigation system errors associated with GPS/augmented GPS are not a function of the runway length (as they are with ILS) and are essentially independent of the range from the airport within the region of interest (0 to 15 nmi). While the augmented GPS NSE is much less than that of ILS, FTE remains the same. For manually flown approaches, a more sensitive deviation display could reduce FTE. This may also be desirable for parallel runway approaches even when flown with an autopilot to more accurately monitor the approach. Refer to Tables 3 and 4 in Attachment #1 for the specific numbers. Attachment # 2 provides a table of ILS localizer beam alignment and bend errors. Adjoining figures at the end of the Appendix graphically depict TSE, NSE and FTE for the various combinations of approaches (ILS, GPS, manual, and autopilot).

ATTACHMENT 1

NASA PARALLEL RUNWAY MONITORING

Task: Determine TSE based on NSE and FTE at 5, 10, and 15 nmi for ILS and GPS

TSE = Total System Error
NSE = Navigation System Error
FTE = Flight Technical Error

$TSE^2 = NSE^2 + FTE^2$ (Independent/Gaussian Assumption)

Note: Full Scale CDI --> +/-2.0045 deg (9000′ RWY)
+/-1.5422 deg (12000′ RWY)

ILS column descriptions for Tables 1 and 2 below:

1. Distance from the runway threshold (nmi)

Navigation System Error (NSE)

2. ILS Localizer Beam Alignment [95% Probability] (ft)
3. ILS Localizer Beam Bends [95% Probability] (ft)
4. Airborne ILS Receiver Error [95% Probability] (ft)
5. Root Sum Square (RSS) of Navigation Error [columns 2, 3, 4] (ft)

[Note: "RSSing" Bias (i.e., alignment) and Random errors is optimistic for overall error distribution]

Flight Technical Error (FTE)

6. Manual Piloting [Assume 1 CDI dot -- 95%] (ft)
7. Manual Piloting [Assume 0.5 CDI dot -- 95%] (ft)
8. Autopilot Error [Assumption -- 95%] (ft)

Total System Error (TSE)

9. Total System Error -- Manual 1 dot CDI [95%] (ft)
10. Total System Error -- Manual 0.5 dot CDI [95%] (ft)
11. Total System Error -- Automatic [95%] (ft)

Table 1: ILS Error Budget for a 9,000 ft Runway

	[Navigation System Error]				[Flight Technical Error]			[Total System Error]		
1) 9000'	RWY, Type I ILS									
Dis(nmi)	ILS Alignmnt	ILS Bm Bends	Air. ILS Rcvr	ILS Nav RSS	Man CDI (1 dot)	Man CDI (0.5 dot)	A_Pilot	TSE Man. (1 dot)	TSE Man. (0.5 dot)	TSE Auto
5	91.1	282.5	36.7	299.1	564.9	282.5	100.0	639.2	411.5	315.4
10	159.7	495.1	64.4	524.2	989.9	495.1	100.0	1120.2	721.0	533.6
15	228.3	707.7	92.0	749.3	1414.9	707.7	100.0	1601.1	1030.6	755.9
2) 9000'	RWY, Type II ILS									
Dis(nmi)	ILS Alignmnt	ILS Bm Bends	Air. ILS Rcvr	ILS Nav RSS	Man CDI (1 dot)	Man CDI (0.5 dot)	A_Pilot	TSE Man. (1 dot)	TSE Man. (0.5 dot)	TSE Auto
5	67.3	282.5	36.7	292.8	564.9	282.5	100.0	636.3	406.9	309.4
10	118.0	495.1	64.4	513.0	989.9	495.1	100.0	1115.0	713.0	522.7
15	168.6	707.7	92.0	733.3	1414.9	707.7	100.0	1593.7	1019.1	740.1
3) 9000'	RWY, Type III ILS									
Dis(nmi)	ILS Alignmnt	ILS Bm Bends	Air. ILS Rcvr	ILS Nav RSS	Man CDI (1 dot)	Man CDI (0.5 dot)	A_Pilot	TSE Man. (1 dot)	TSE Man. (0.5 dot)	TSE Auto
5	26.9	282.5	36.7	286.2	564.9	282.5	100.0	633.3	402.2	303.2
10	47.2	495.1	64.4	501.5	989.9	495.1	100.0	1109.7	704.7	511.4
15	67.4	707.7	92.0	716.8	1414.9	707.7	100.0	1586.2	1007.3	723.8

Table 2: ILS Error Budget for a 12,000 ft Runway

	[Navigation System Error]				[Flight Technical Error]			[Total System Error]		
1) 12000′	RWY, Type I ILS									
Dis(nmi)	ILS Algnmnt	ILS Bm Bends	Air. ILS Rcvr	ILS Nav RSS	Man CDI (1 dot)	Man CDI (0.5 dot)	A_Pilot	TSE Man. (1 dot)	TSE Man. (0.5 dot)	TSE Auto
5	75.4	233.4	30.4	247.2	467.2	233.6	100.0	528.6	340.1	266.6
10	128.1	396.9	51.6	420.3	794.4	397.1	100.0	898.7	578.2	432.0
15	180.9	560.4	72.9	593.3	1121.6	560.7	100.0	1268.9	816.4	601.7
2) 12000′	RWY, Type II ILS									
Dis(nmi)	ILS Algnmnt	ILS Bm Bends	Air. ILS Rcvr	ILS Nav RSS	Man CDI (1 dot)	Man CDI (0.5 dot)	A_Pilot	TSE Man. (1 dot)	TSE Man. (0.5 dot)	TSE Auto
5	55.7	233.4	30.4	241.9	467.2	233.6	100.0	526.1	336.2	261.7
10	94.6	396.9	51.6	411.3	794.4	397.1	100.0	894.5	571.7	423.3
15	133.6	560.4	72.9	580.7	1121.6	560.7	100.0	1263.0	807.2	589.2
3) 12000′	RWY, Type III ILS									
Dis(nmi)	ILS Algnmnt	ILS Bm Bends	Air. ILS Rcvr	ILS Nav RSS	Man CDI (1 dot)	Man CDI (0.5 dot)	A_Pilot	TSE Man. (1 dot)	TSE Man. (0.5 dot)	TSE Auto
5	22.3	233.4	30.4	236.4	467.2	233.6	100.0	523.6	332.3	256.7
10	37.8	396.9	51.6	402.0	794.4	397.1	100.0	890.3	565.1	414.3
15	53.4	560.4	72.9	567.6	1121.6	560.7	100.0	1257.0	797.8	576.4

GPS Error Budget Summary

GPS column descriptions for Tables 3 and 4 below:

1. Distance from the runway threshold (nmi)
2. GPS Navigation System Error (Horizontal) [95%] (ft)
3. Manual Piloting [Assume 1 CDI dot -- 95%] (ft)
4. Manual Piloting [Assume 0.5 CDI dot -- 95%] (ft)
5. Autopilot Error [Assumption -- 95%] (ft)
6. Total System Error -- Manual 1 dot CDI [95%] (ft)
7. Total System Error -- Manual 0.5 dot CDI [95%] (ft)
8. Total System Error -- Automatic [95%] (ft)

Assumption: GPS errors are essentially constant over the region of interest (i.e., 0 to 15 nmi)

[Navigation System Error (ft) -- 95%]

Approach	Std. GPS Posn.	FAA LAAS Rqmt
Non Prec	328.0	--
CAT I	--	25.9
CAT II	--	18.0
CAT III	--	TBD

Table 3: GPS Error Budget for a 9,000 ft Runway

	[NSE]	[Flight Technical Error]			[Total System Error]		
1) 9000' RWY, Standard GPS							
Dis(nmi)	Std. GPS	Man CDI (1 dot)	Man CDI (0.5 dot)	A_Pilot	TSE Man. (1 dot)	TSE Man. (0.5 dot)	TSE Auto
5	328.0	564.9	282.5	100.0	653.2	432.9	342.9
10	328.0	989.9	495.1	100.0	1042.9	593.9	342.9
15	328.0	1414.9	707.7	100.0	1452.5	780.0	342.9
2) 9000' RWY, Augmented GPS (CAT I Accuracy)							
Dis(nmi)	Aug. GPS	Man CDI (1 dot)	Man CDI (0.5 dot)	A_Pilot	TSE Man. (1 dot)	TSE Man. (0.5 dot)	TSE Auto
5	25.9	564.9	282.5	100.0	565.5	283.7	103.3
10	25.9	989.9	495.1	100.0	990.3	495.8	103.3
15	25.9	1414.9	707.7	100.0	1415.2	708.2	103.3
3) 9000' RWY, Augmented GPS (CAT II Accuracy)							
Dis(nmi)	Aug. GPS	Man CDI (1 dot)	Man CDI (0.5 dot)	A_Pilot	TSE Man. (1 dot)	TSE Man. (0.5 dot)	TSE Auto
5	18.0	564.9	282.5	100.0	565.2	283.1	101.6
10	18.0	989.9	495.1	100.0	990.1	495.4	101.6
15	18.0	1414.9	707.7	100.0	1415.1	707.9	101.6
4) 9000' RWY, Augmented GPS (CAT III Accuracy)							
Dis(nmi)	Aug. GPS	Man CDI (1 dot)	Man CDI (0.5 dot)	A_Pilot	TSE Man. (1 dot)	TSE Man. (0.5 dot)	TSE Auto
5	TBD	564.9	282.5	100.0	TBD	TBD	TBD
10	TBD	989.9	495.1	100.0	TBD	TBD	TBD
15	TBD	1414.9	707.7	100.0	TBD	TBD	TBD

Table 4: GPS Error Budget for a 12,000 ft Runway

	[NSE]	[Flight Technical Error]			[Total System Error]		
1) 12000′ RWY, Standard GPS							
Dis(nmi)	Std. GPS	Man CDI (1 dot)	Man CDI (0.5 dot)	A_Pilot	TSE Man. (1 dot)	TSE Man. (0.5 dot)	TSE Auto
5	328.0	467.2	233.6	100.0	570.8	402.7	342.9
10	328.0	794.4	397.1	100.0	859.4	515.1	342.9
15	328.0	1121.6	560.7	100.0	1168.6	649.6	342.9
2) 12000′ RWY, Augmented GPS (CAT I Accuracy)							
Dis(nmi)	Aug. GPS	Man CDI (1 dot)	Man CDI (0.5 dot)	A_Pilot	TSE Man. (1 dot)	TSE Man. (0.5 dot)	TSE Auto
5	25.9	467.2	233.6	100.0	467.9	235.0	103.3
10	25.9	794.4	397.1	100.0	794.8	398.0	103.3
15	25.9	1121.6	560.7	100.0	1121.9	561.3	103.3
3) 12000′ RWY, Augmented GPS (CAT II Accuracy)							
Dis(nmi)	Aug. GPS	Man CDI (1 dot)	Man CDI (0.5 dot)	A_Pilot	TSE Man. (1 dot)	TSE Man. (0.5 dot)	TSE Auto
5	18.0	467.2	233.6	100.0	467.5	234.3	101.6
10	18.0	794.4	397.1	100.0	794.6	397.5	101.6
15	18.0	1121.6	560.7	100.0	1121.7	561.0	101.6
4) 12000′ RWY, Augmented GPS (CAT III Accuracy)							
Dis(nmi)	Aug. GPS	Man CDI (1 dot)	Man CDI (0.5 dot)	A_Pilot	TSE Man. (1 dot)	TSE Man. (0.5 dot)	TSE Auto
5	TBD	467.2	233.6	100.0	TBD	TBD	TBD
10	TBD	794.4	397.1	100.0	TBD	TBD	TBD
15	TBD	1121.6	560.7	100.0	TBD	TBD	TBD

Notes:

1. 9000′ Runway: 0.155 DDM = 150 microamps = 2.0045 deg
2. 12000′ Runway: 0.155 DDM = 150 microamps = 1.5422 deg
3. ILS Localizer Beam Alignment at the ILS Reference Datum [99.7%]:
    - Type I : 10.5 m or the linear equivalent of 0.015 DDM
    - Type II : 7.5 m
    - Type III: 3.0 m
4. ILS Localizer Beam Bends (Beyond 4nmi) = 0.031 DDM [95%]
5. Airborne ILS Receiver Error -- 5% of the Standard Deflection (Std. Deflection = 78 microamps) [95%]

References:
1) ICAO Annex 10 (21/11/85, Sections 3.1.3.4.1 & 3.1.3.6.1, p.10,11)
2) RTCA/DO-117 (page 3)
3) FAA Local Area Augmentation System (LAAS) RFP (2/17/95)

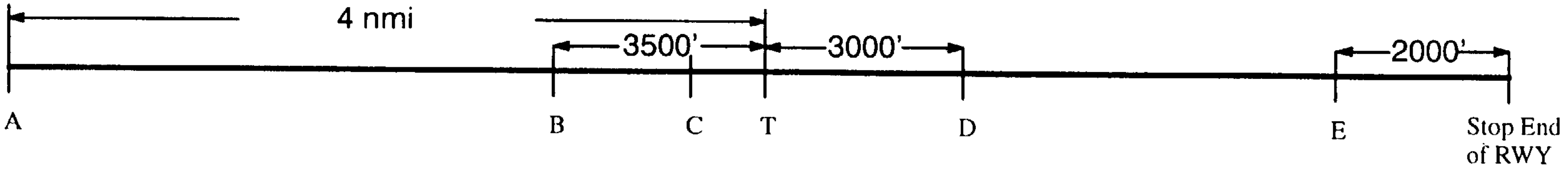
ILS Localizer Beam *(Alignment and Bends — 95% Probability)*

		Type I		Type II / III	
	ILS Points \ RWY Length	9000' Runway	12,000' Runway	9000' Runway	12,000' Runway
Align-ment		0.1293°	0.0995°	0.0955° *(CAT II)* 0.0382° *(CAT III)*	0.0735° *(CAT II)* 0.0294° *(CAT III)*
Beam Bends	Beyond A	0.4009°	0.3083°	0.4009°	0.3083°
	A -> B	0.4009° -> 0.1940°	0.3083° -> 0.1492°	0.4009° -> 0.0647°	0.3083° -> 0.0497°
	B -> C	0.1940°	0.1492°	——	——
	B -> T	——	——	0.0647°	0.0497°
	T -> D	——	——	0.0647° *(CAT III)*	0.0497° *(CAT III)*
	D -> E	——	——	0.0647° -> 0.1294° *(CAT III)*	0.0497° -> 0.0994° *(CAT III)*

ILS pts:
- A. 4 nmi from threshold (Outer Marker)
- B. 3500 ft from threshold which is ≈ 200 ft above threshold (Middle Marker)
- C. 100 ft above threshold (Inner Marker)
- T. Threshold
- D. Runway (3000 ft down runway from the threshold)
- E. Runway (2000 ft from the stop end of the runway)

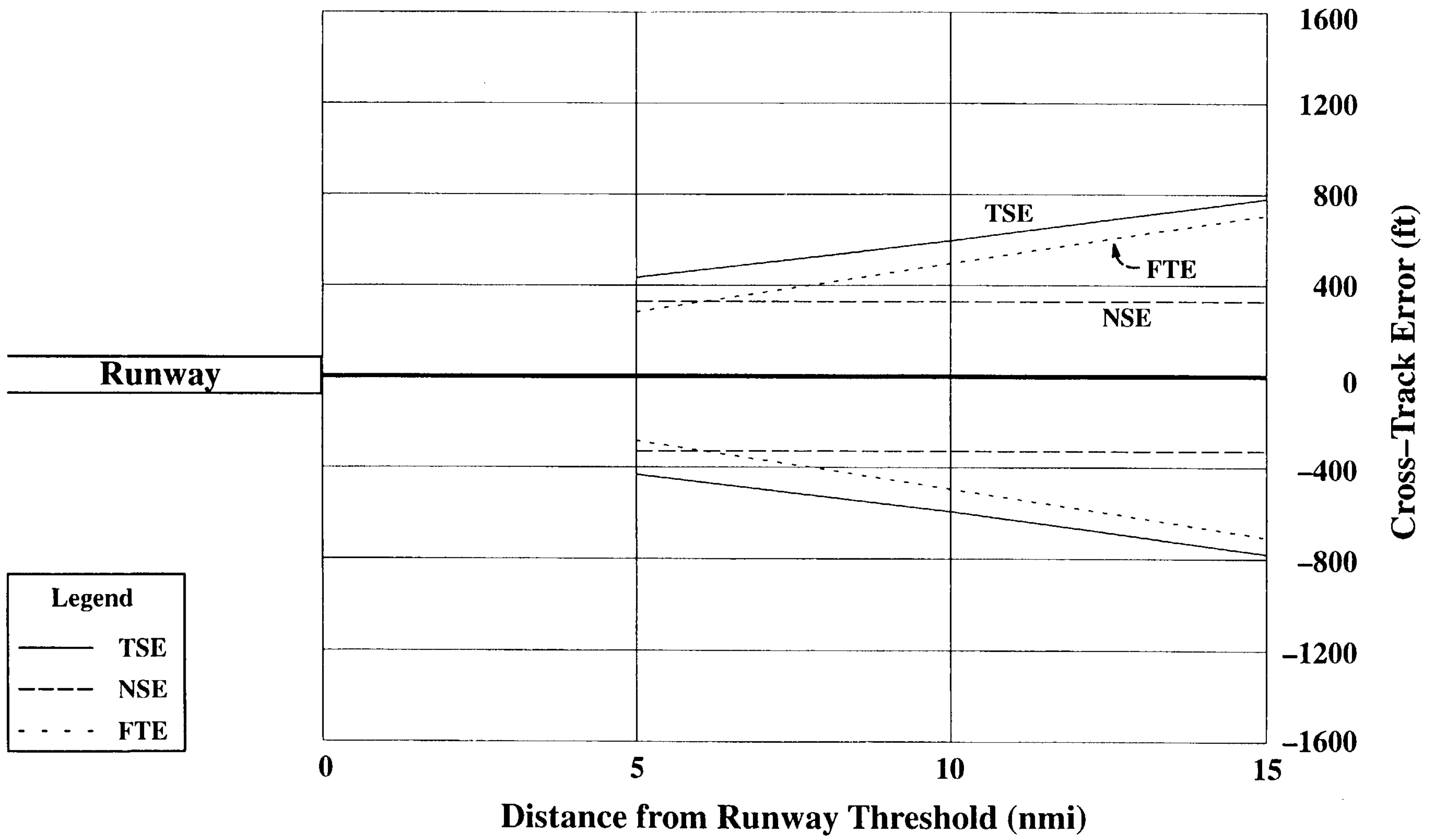
Notation: For general ILS points X and Y, "X -> Y" indicates that the spec. at ILS point X descreases at a linear rate to spec. at ILS point Y.

Reference: ICAO Annex 10 (21/11/85, Sections 3.1.3.4.1 & 3.1.3.6.1 , p. 10, 11)



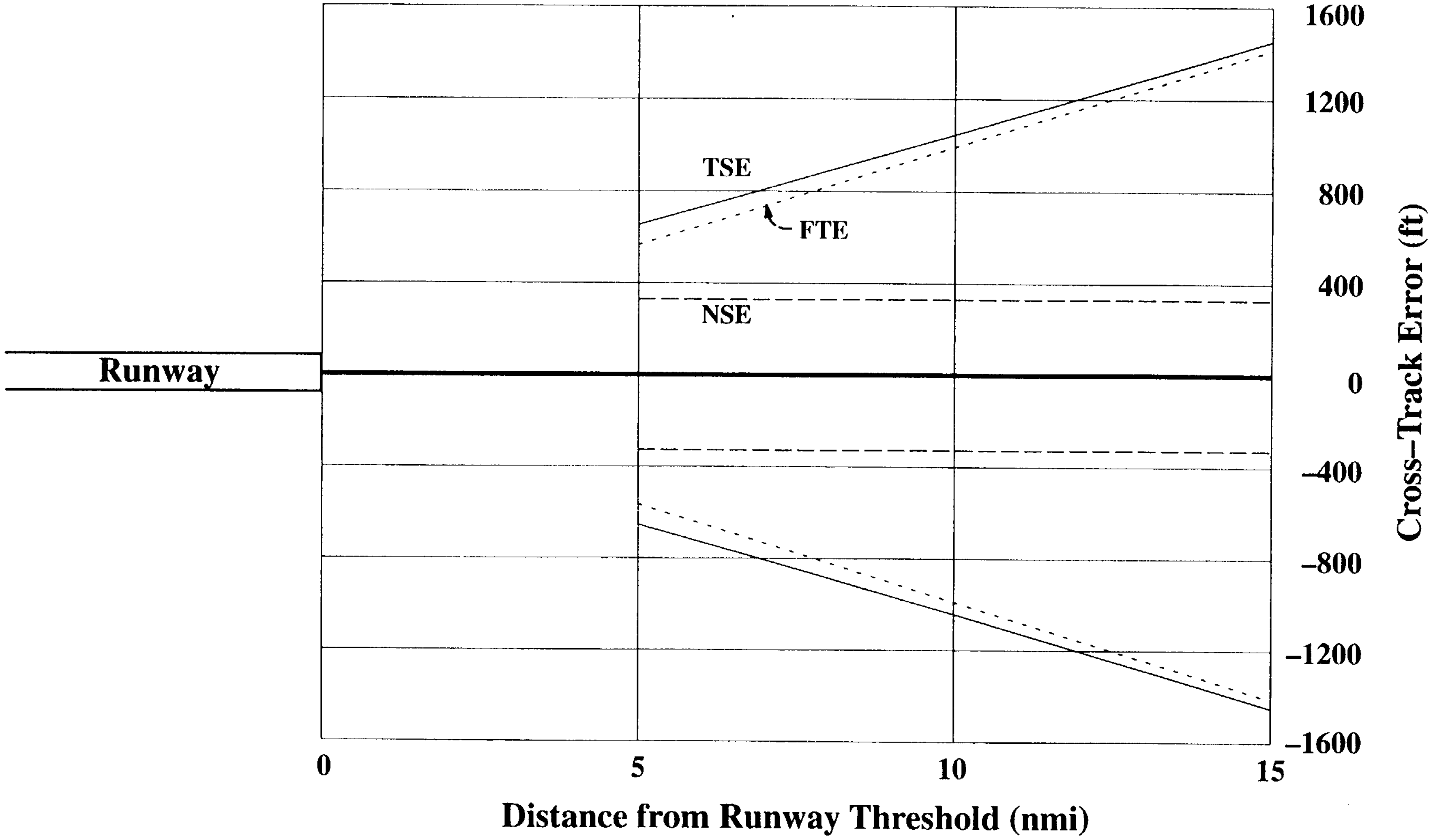
Approach/Landing Cross–Track Errors

Approach Scenario: Standard GPS, Manual (1/2 dot), 9000' Runway



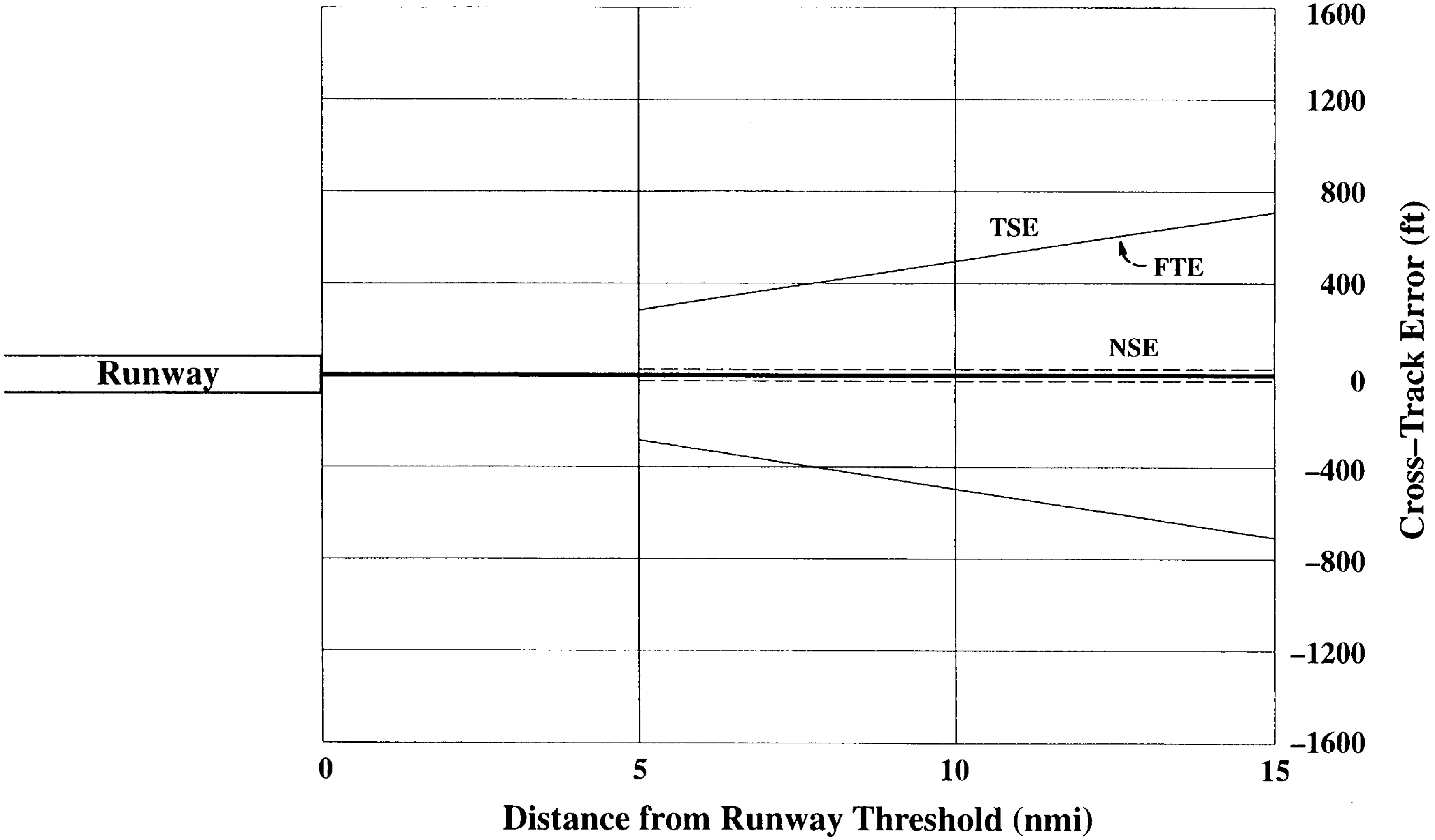
Approach/Landing Cross–Track Errors

Approach Scenario: Standard GPS, Manual (1 dot), 9000' Runway



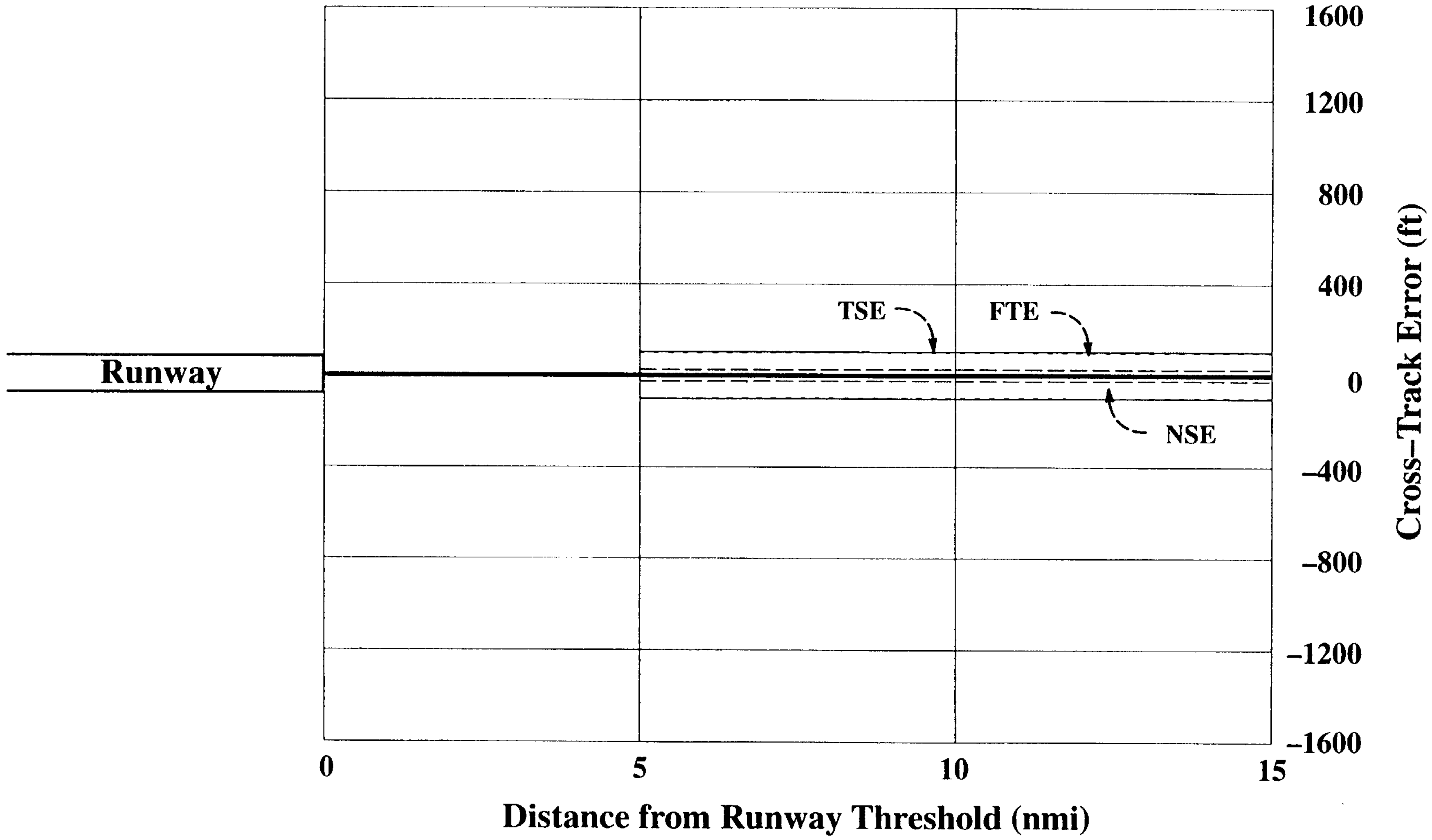
Approach/Landing Cross–Track Errors

Approach Scenario: GPS Cat. I, Manual (1/2 dot), 9000’ Runway



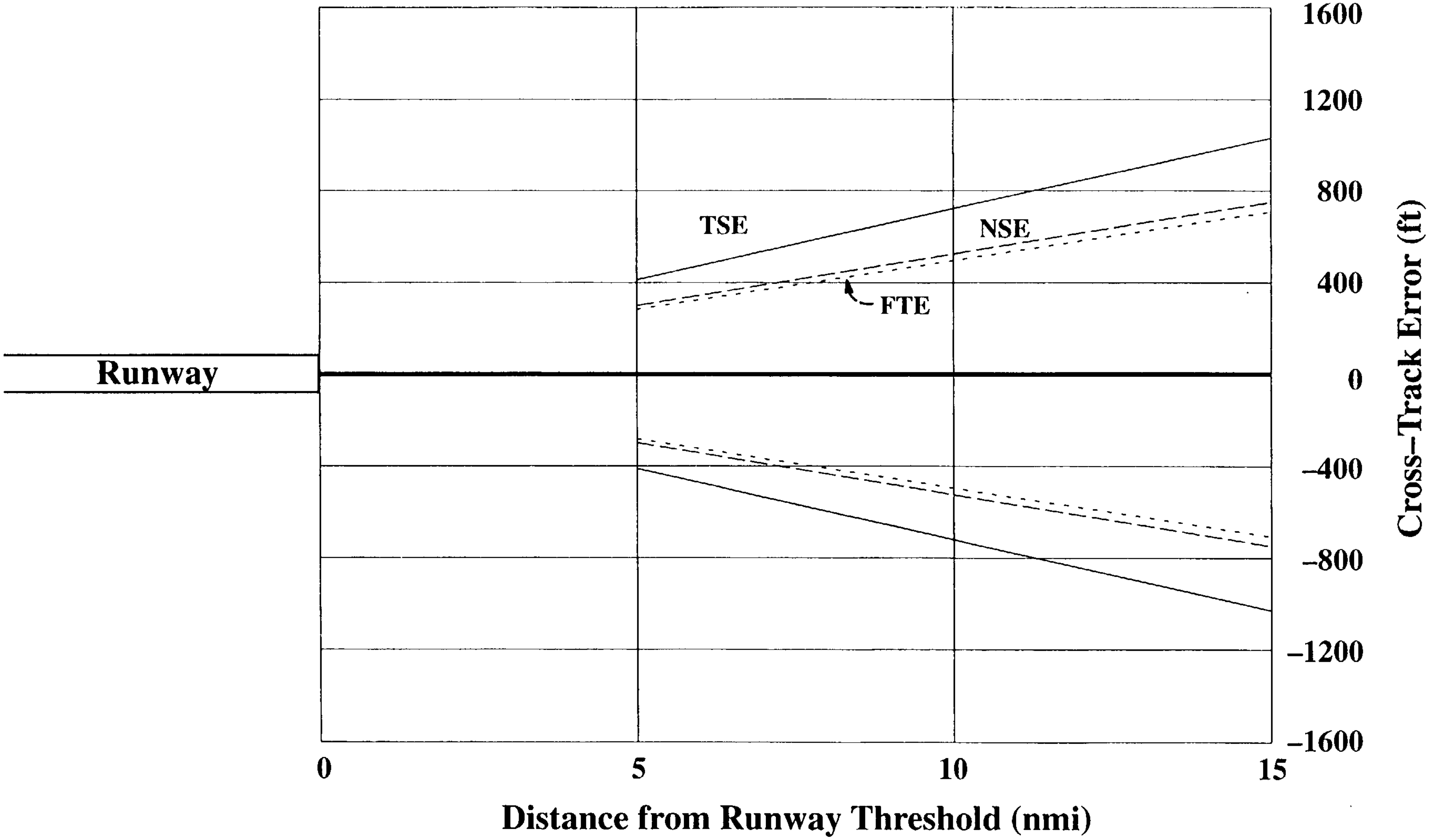
Approach/Landing Cross–Track Errors

Approach Scenario: GPS Cat. I, Autopilot, 9000' Runway



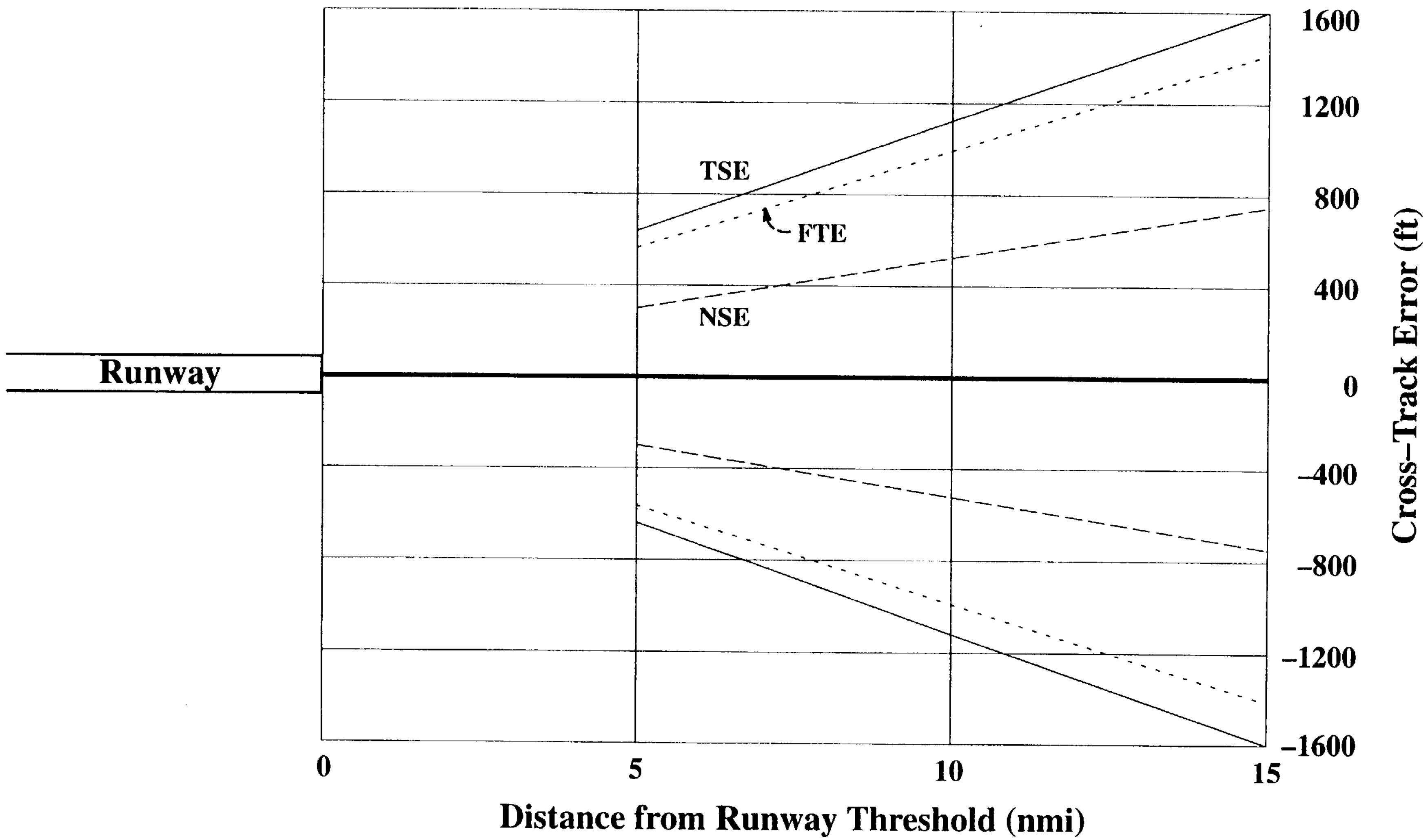
Approach/Landing Cross–Track Errors

Approach Scenario: Type I ILS, Manual (1/2 dot), 9000' Runway



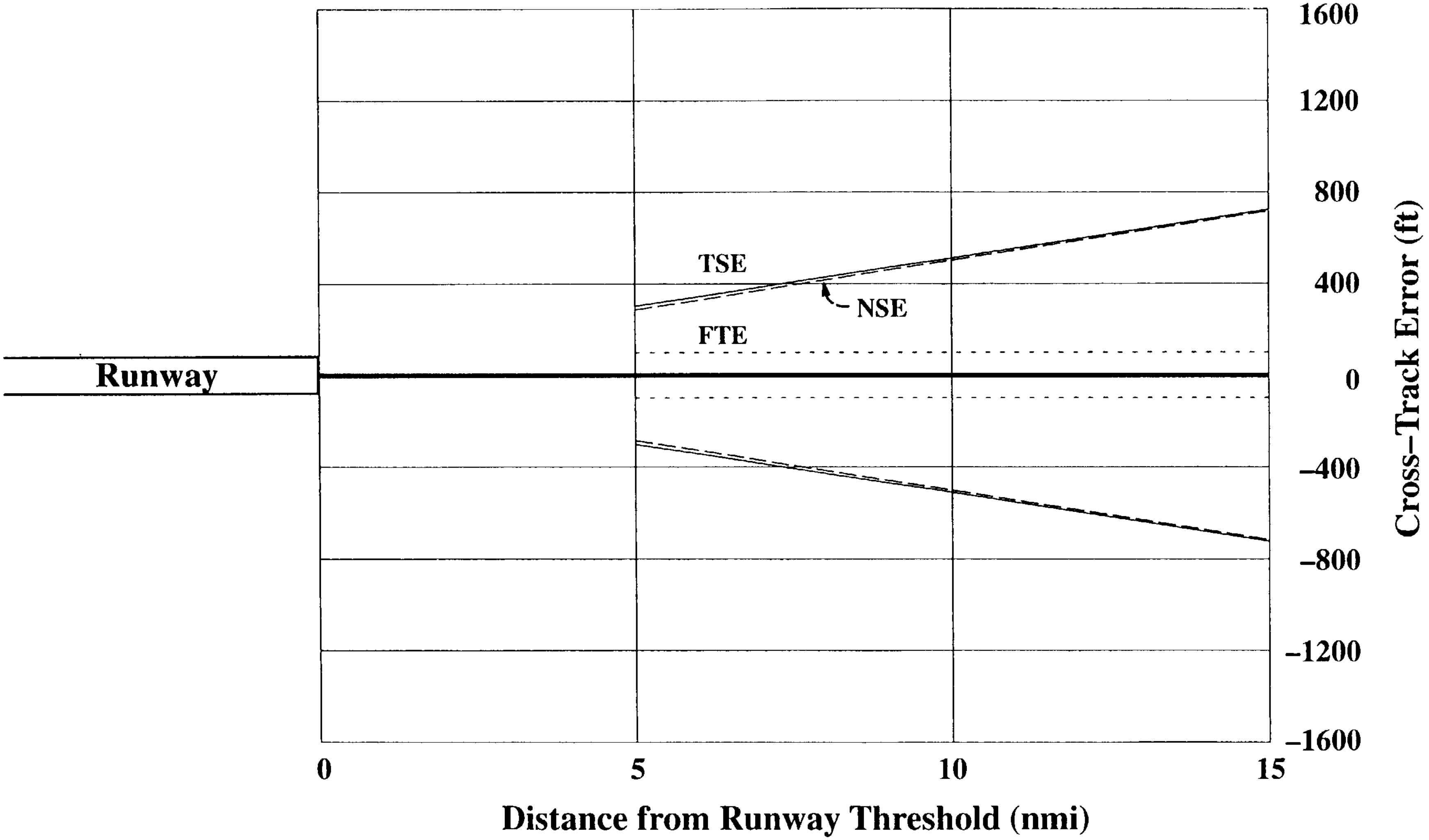
Approach/Landing Cross–Track Errors

Approach Scenario: Type I ILS, Manual (1 dot), 9000’ Runway

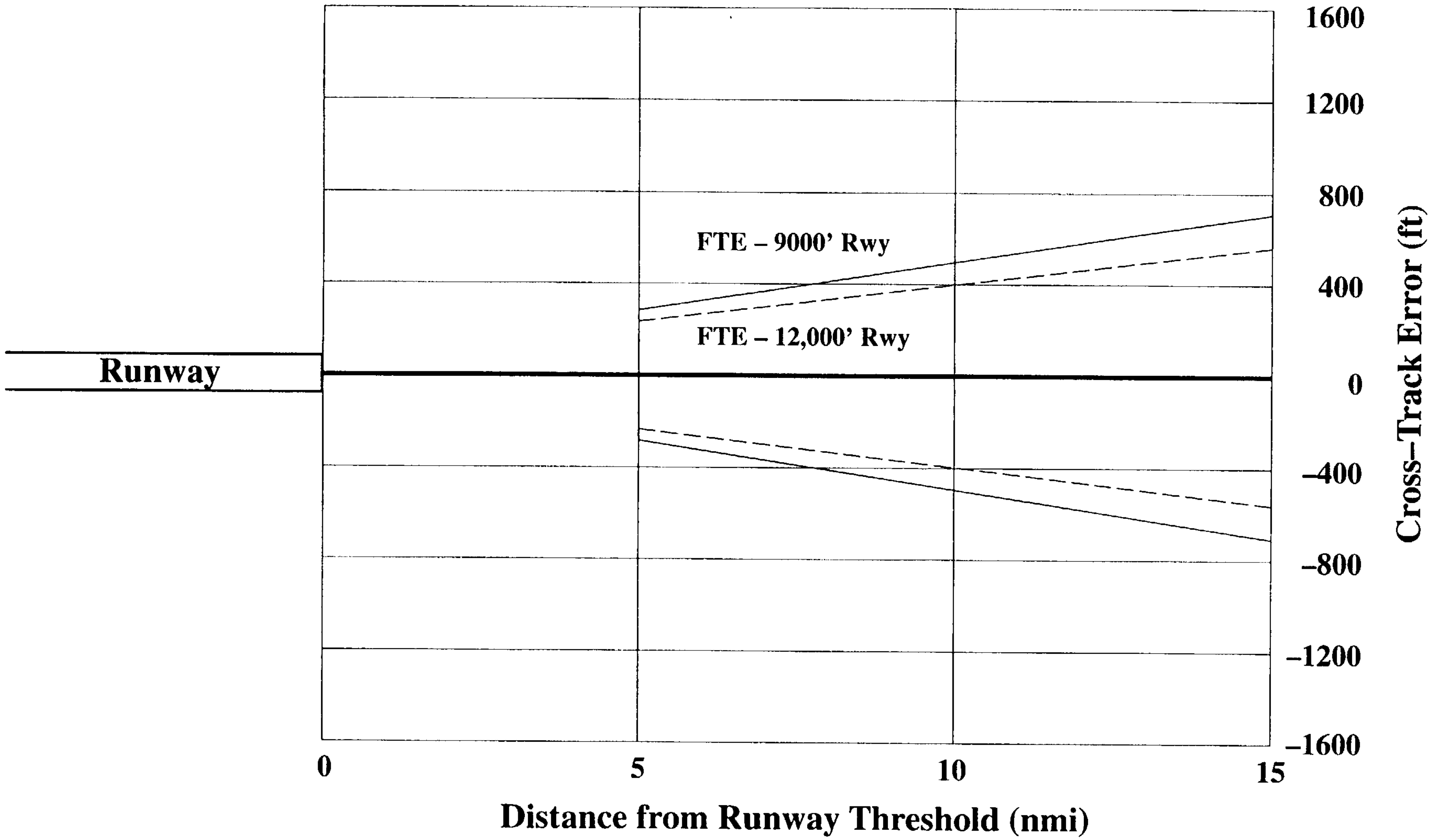


Approach/Landing Cross–Track Errors

Approach Scenario: Type III ILS, Autopilot, 9000’ Runway

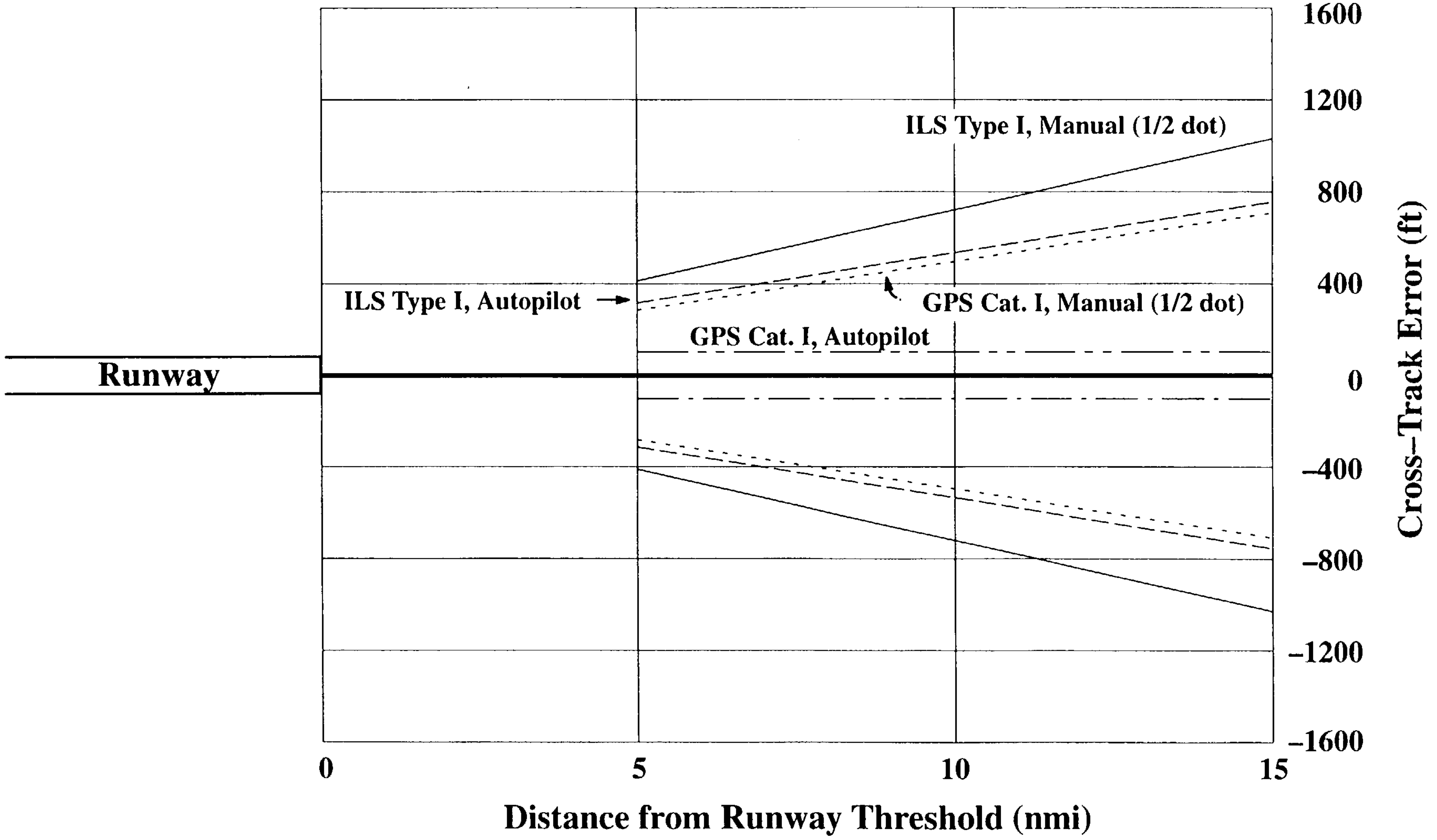


FTE vs Runway Length — 1/2 Dot Manual Approach



Summary of the Total System Errors (TSE)

9,000 ft Runway



Appendix C

Flight Track Templates used for AILS Alerting Simulations

Appendix C documents the flight track templates that used were used in the AILS Monte Carlo simulations presented in this report. Flight track templates were produced via pilot flown runway approaches using Collins AT&E's Fokker 70 part-task simulator. Normal, blunder and fake blunder approaches were flown. The following describe the approach/landing flight track generation methodology and associated constraints:

- A side-stick controller was utilized as the airplane control device.
- Autothrottle was turned on.
- Rudder pedals were unavailable.
- Pilot flew to course deviation dots on PFD, i.e., no flight director guidance was used.
- The ILS signal did not include effects of beam alignment and beam bend errors.
- All flight tracks were flown in fog, i.e., at least Cat I conditions.
- Flight tracks were flown in moderate wind gusts (12.5 knots) using JAR All Weather Operations (AWO) model; (x, y, z wind gusts); no steady state cross wind components were included.
- 8 flight track scenarios were flown.
- Each scenario was flown at 3 speeds (130, 145 and 160 knots).
- State variables recorded for each scenario are x, y, z position, bank angle/roll, pitch angle, heading/yaw, and ground speed.

The following Flight Track Template Scenarios were flown:

1. Normal approach/landing - "FNRM"
2. 30^0 heading blunder - "FB30"
3. 15^0 heading blunder - "FB15"
4. Constant 5^0 bank angle blunder - "FSB5"
5. Slow 10^0 heading change blunder - "FSLO"
6. Slow 5^0 heading change blunder - "FSH5"
7. Fake blunder toward evader runway - "FFAK"
8. Intruder drifts away from own and evader's runway, recognizes error and subsequently over adjusts causing a fake blunder - "FADJ"

Note - All scenarios commenced with a standard 30 degree intercept of localizer.

The following figures document the above flight track scenarios.

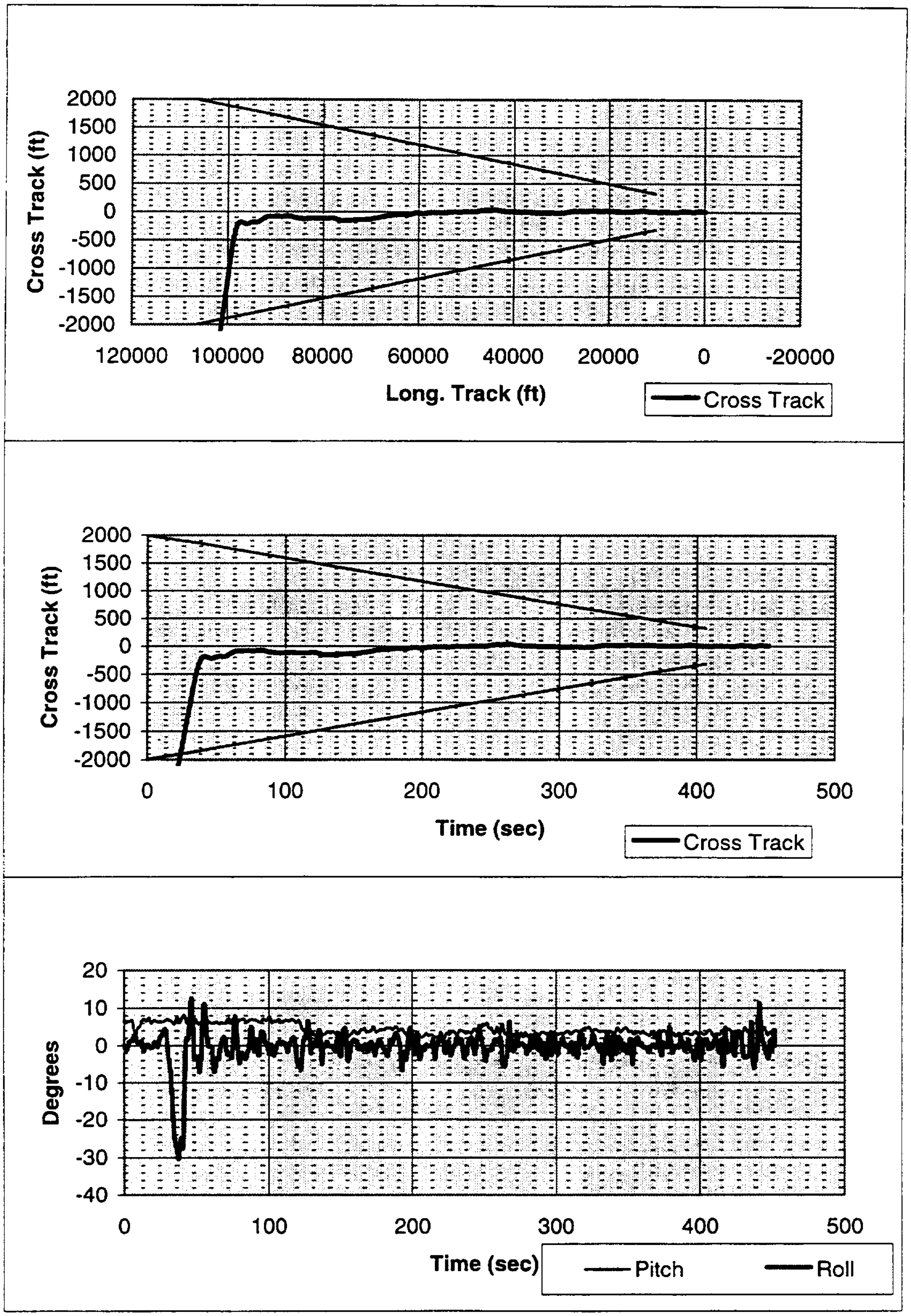


Figure C-1A Normal Approach "FNRM"
(130 knot Ground Speed, 12.5 knot Wind Gusts, Fog)

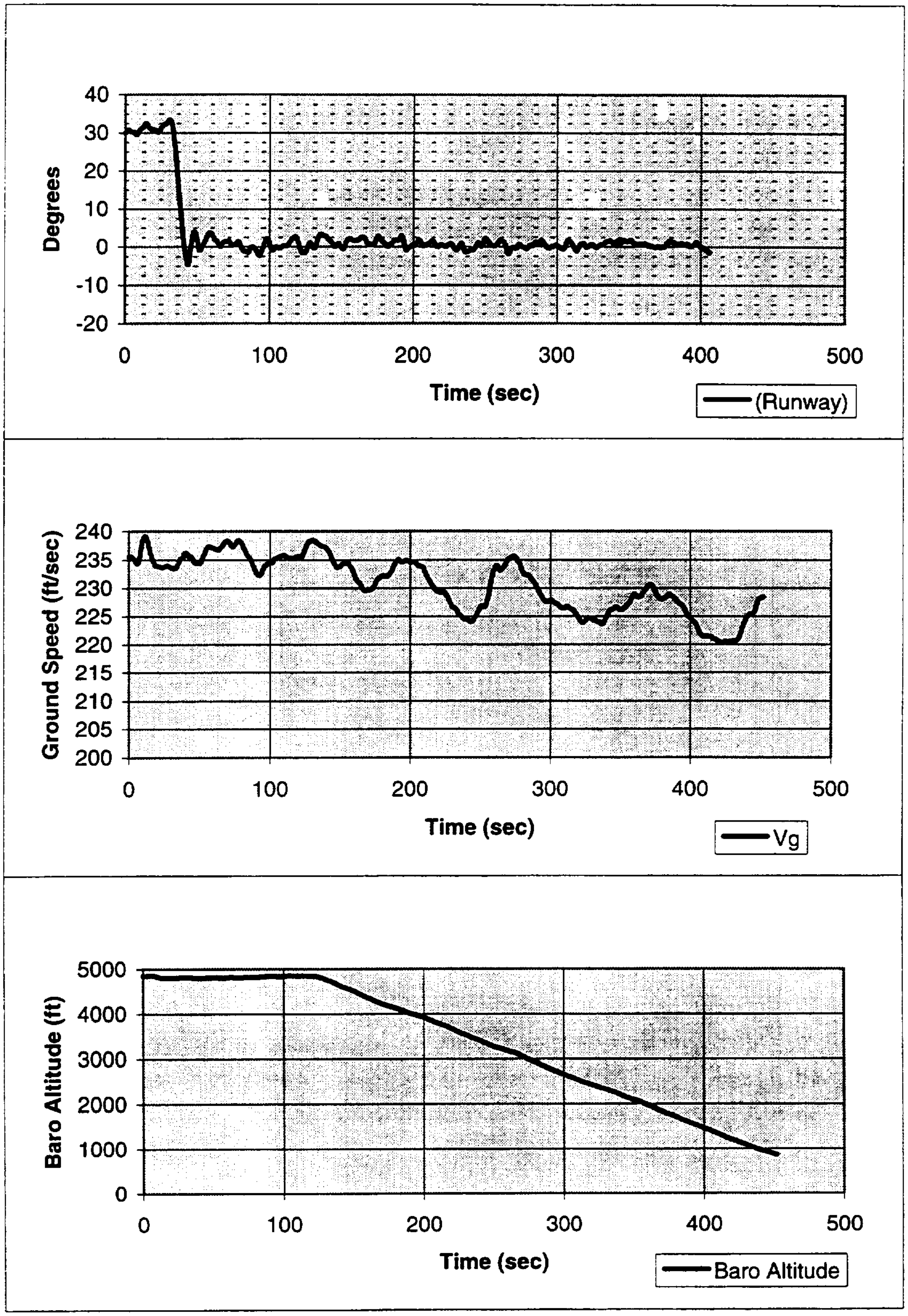


Figure C-1B Normal Approach "FNRM"
(130 knot Ground Speed, 12.5 knot Wind Gusts, Fog)

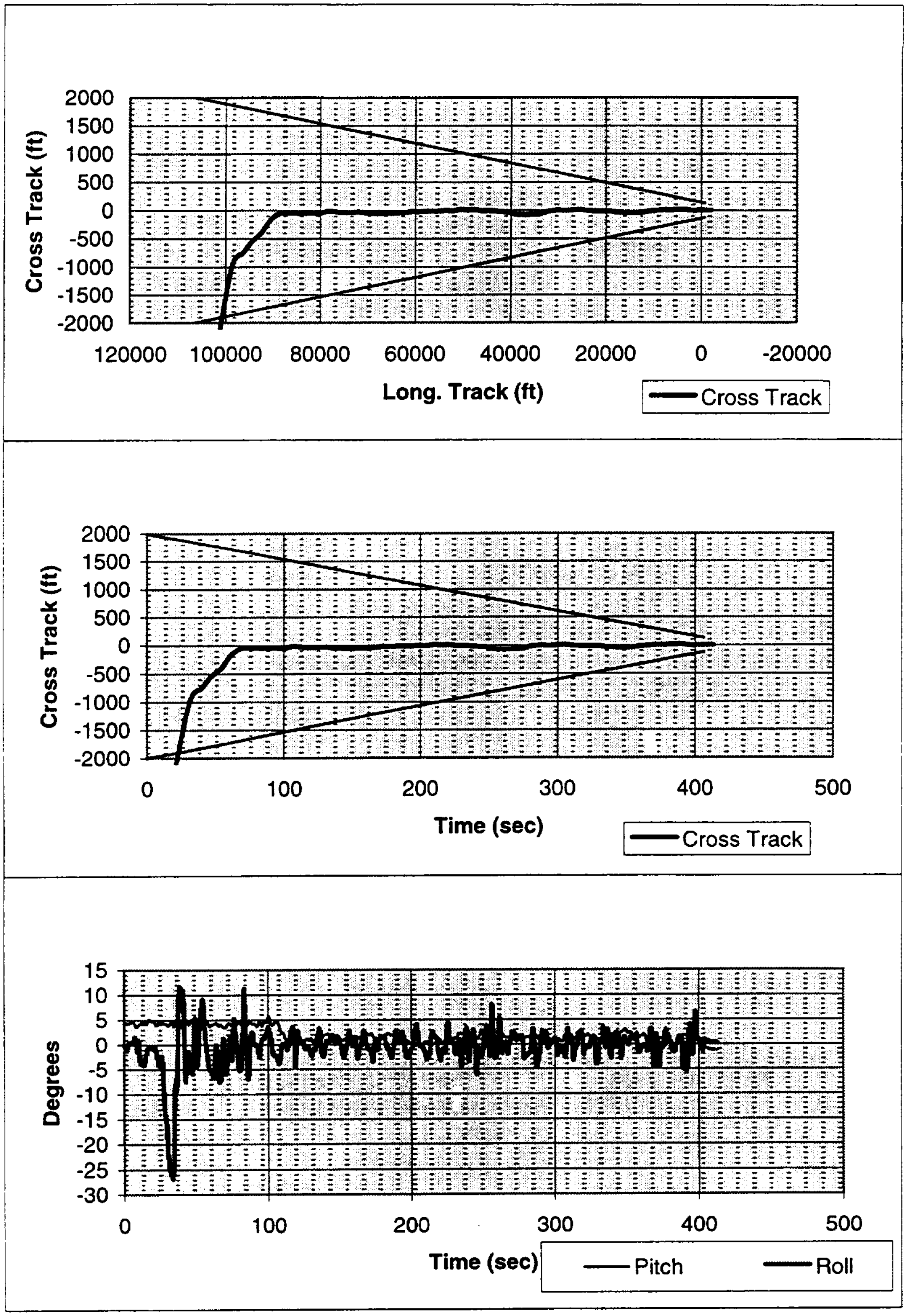


Figure C-2A Normal Approach "FNRM"
(145 knot Ground Speed, 12.5 knot Wind Gusts, Fog)

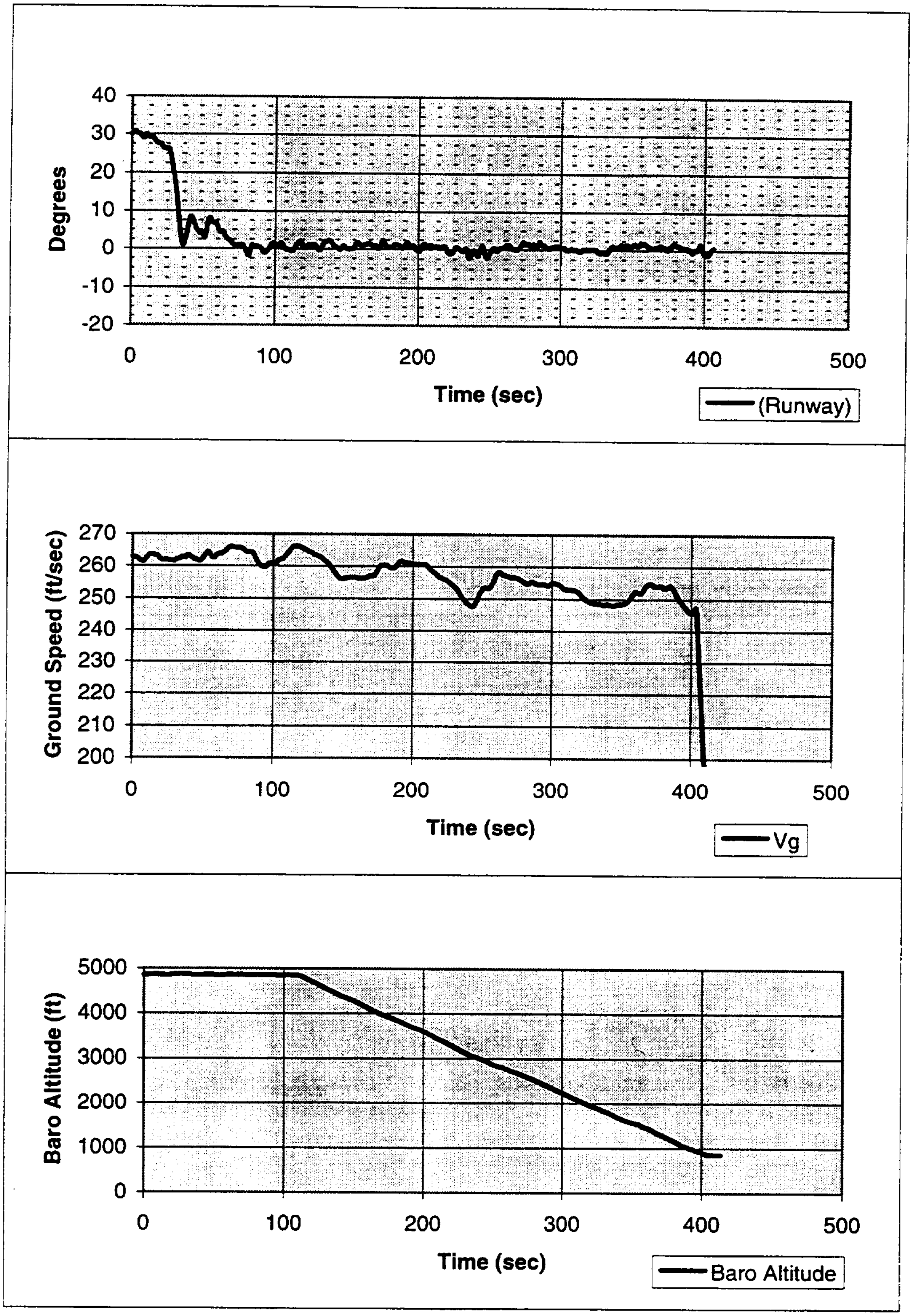


Figure C-2B Normal Approach "FNRM"
(145 knot Ground Speed, 12.5 knot Wind Gusts, Fog)

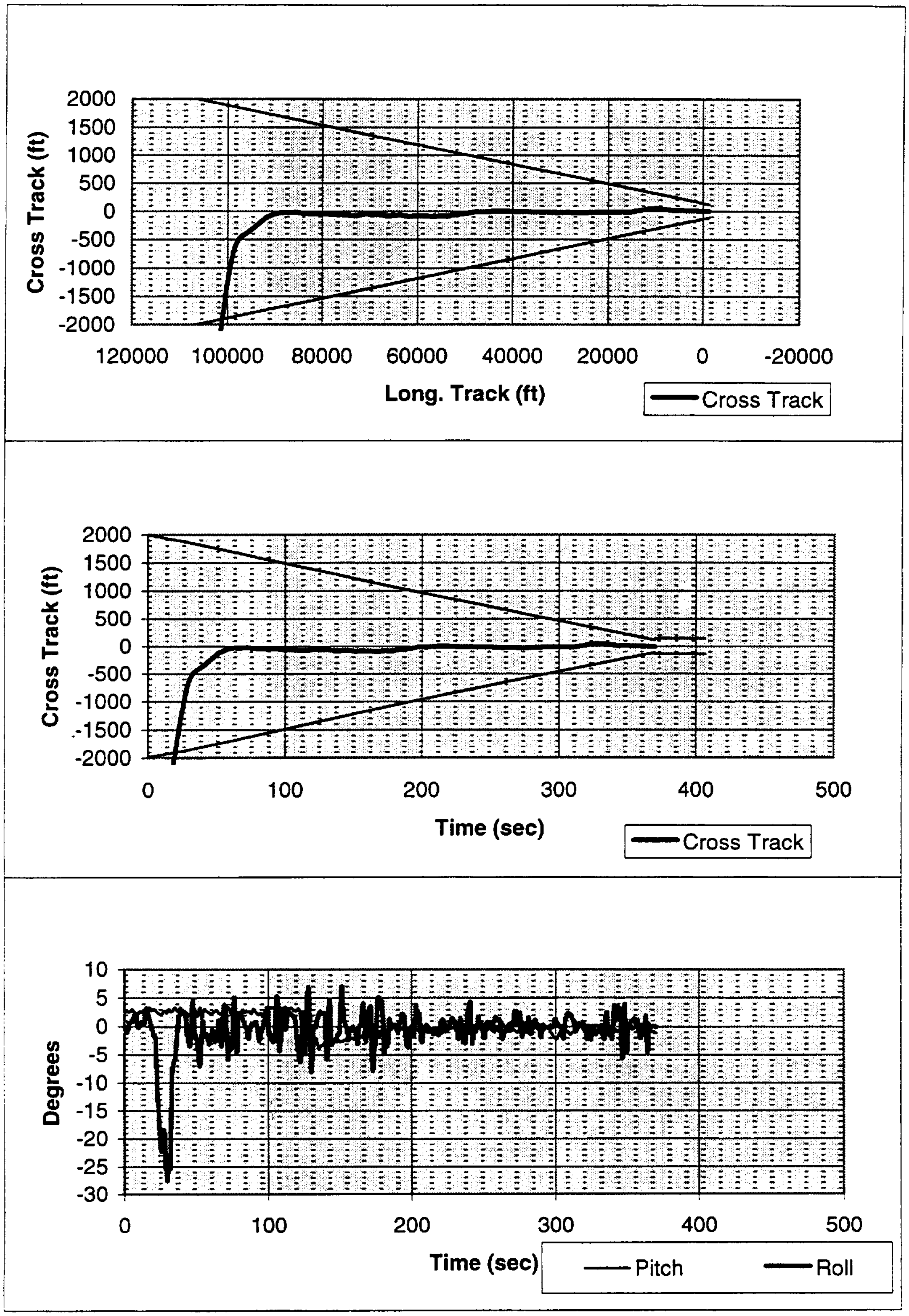


Figure C-3A Normal Approach "FNRM"
(160 knot Ground Speed, 12.5 knot Wind Gusts, Fog)

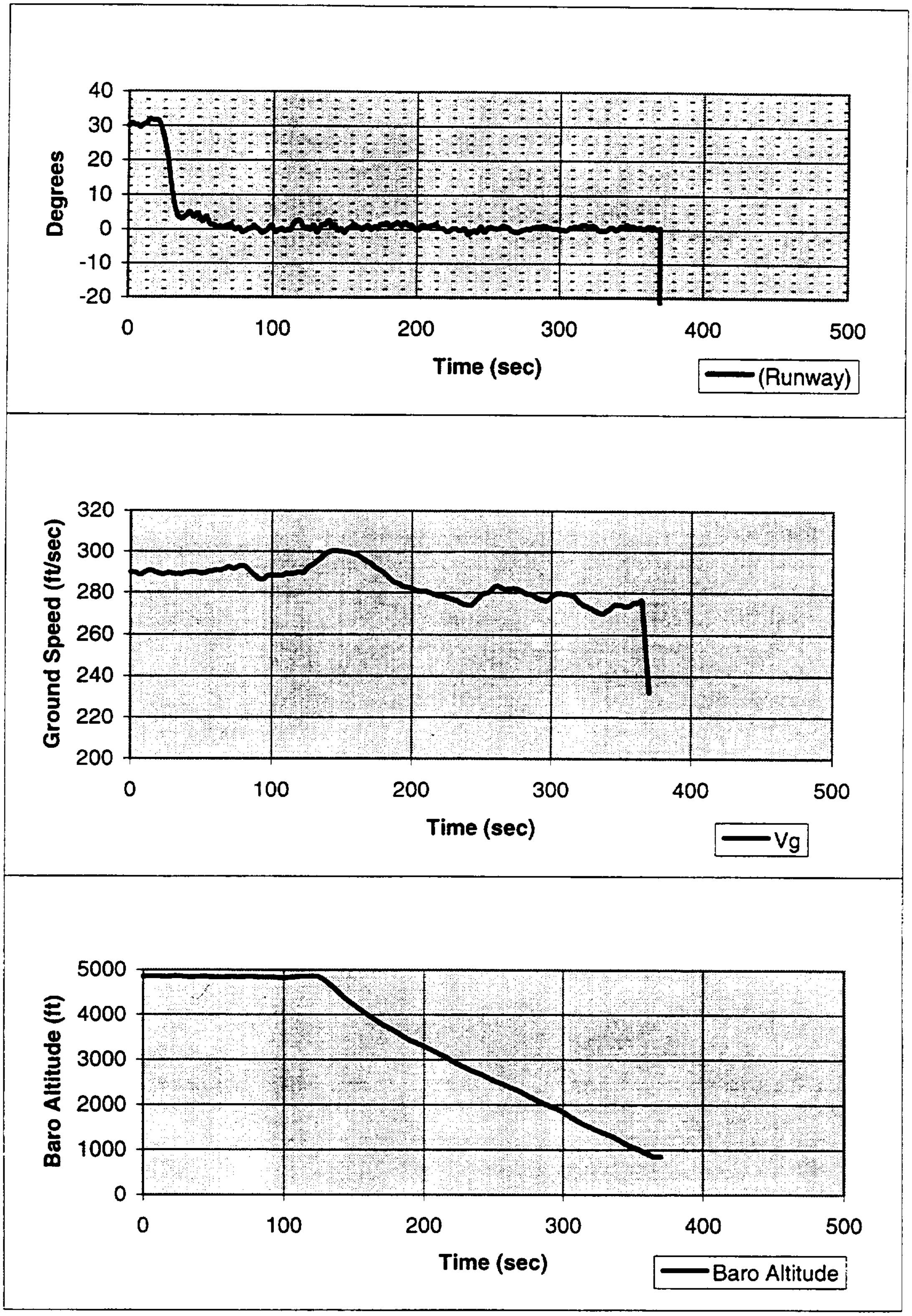


Figure C-3B Normal Approach "FNRM"
(160 knot Ground Speed, 12.5 knot Wind Gusts, Fog)

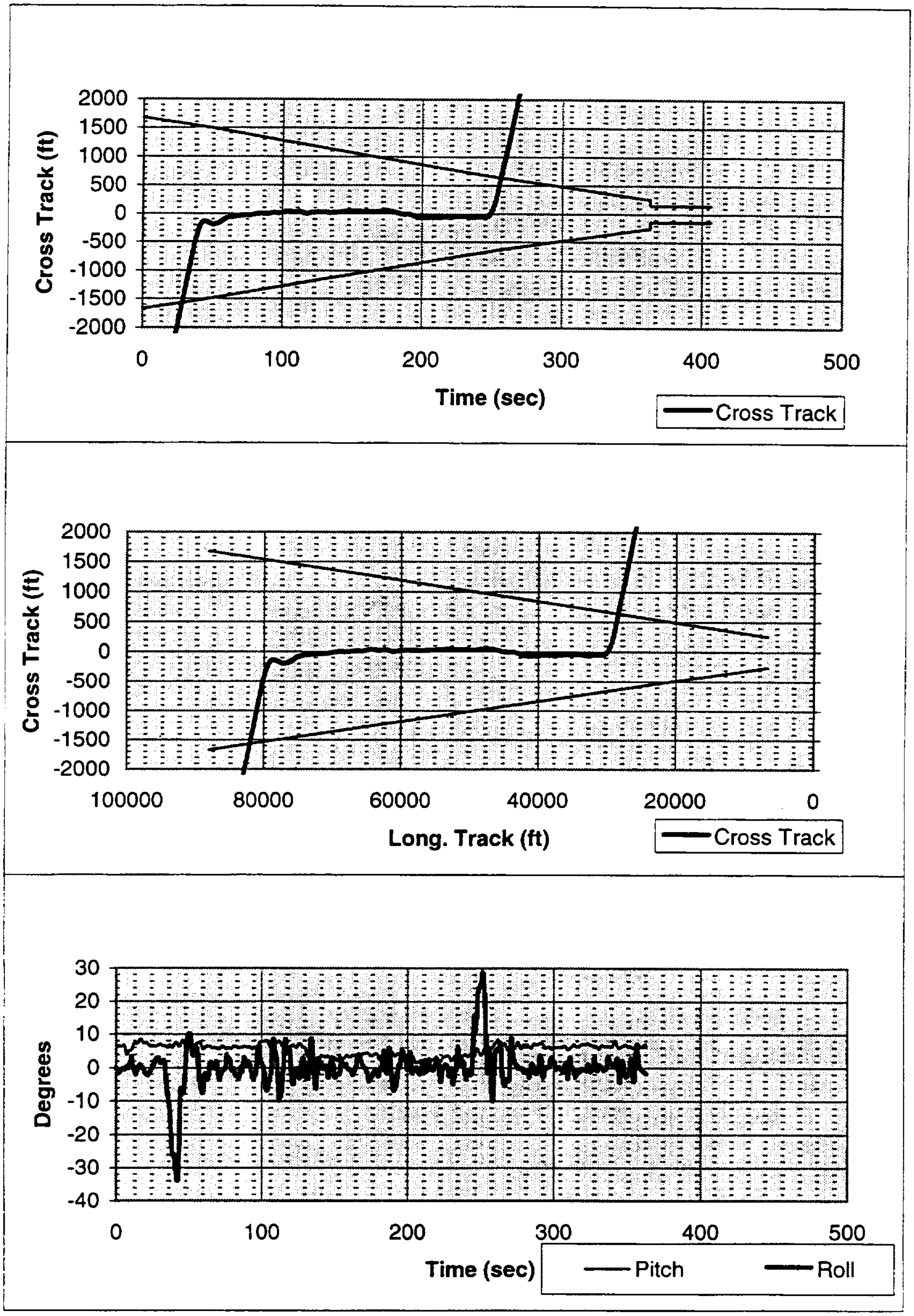


Figure C-4A 30 Degree Heading Blunder "FB30"
(130 knot Ground Speed, 12.5 knot Wind Gusts, Fog)

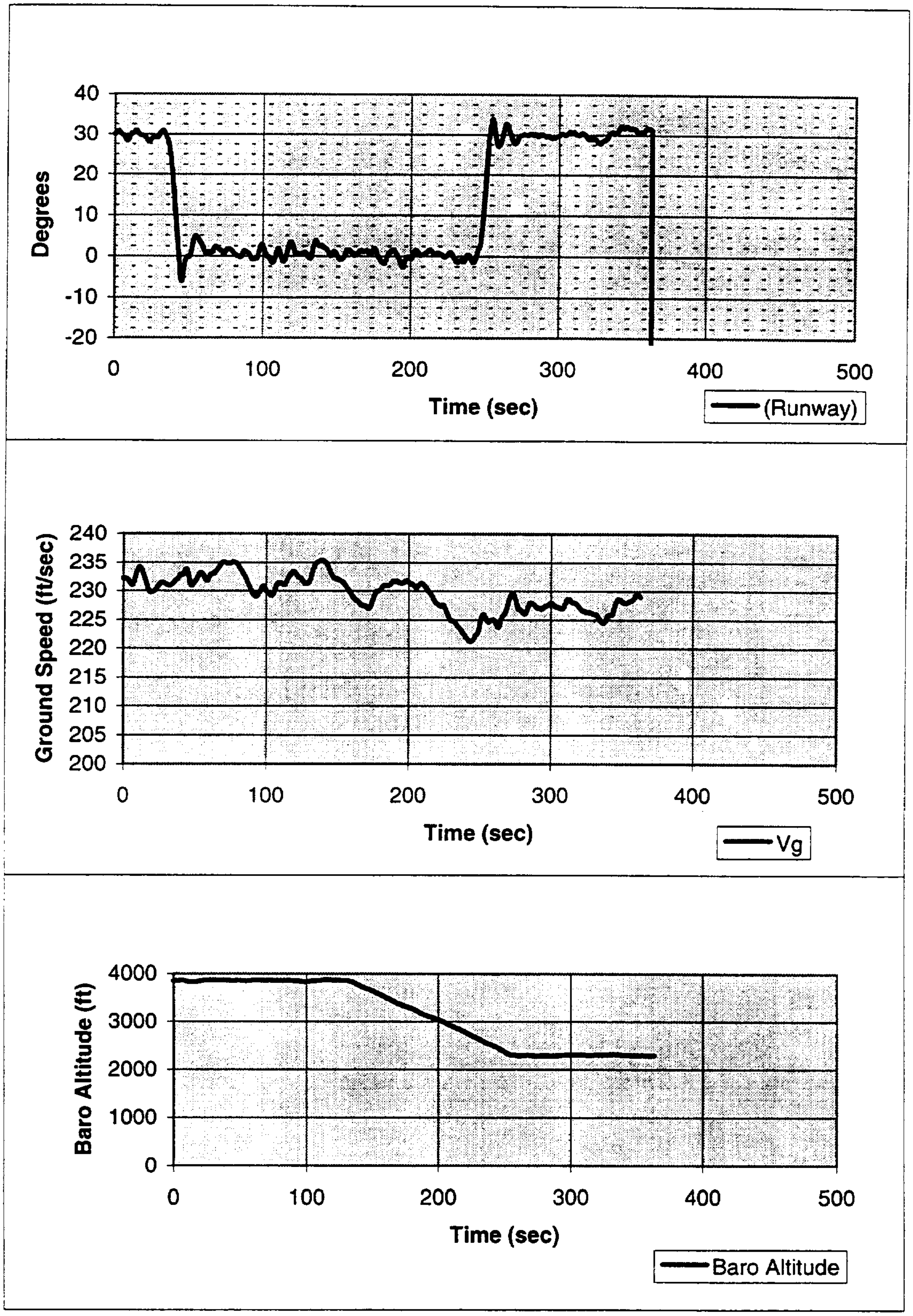


Figure C-4B 30 Degree Heading Blunder "FB30"
(130 knot Ground Speed, 12.5 knot Wind Gusts, Fog)

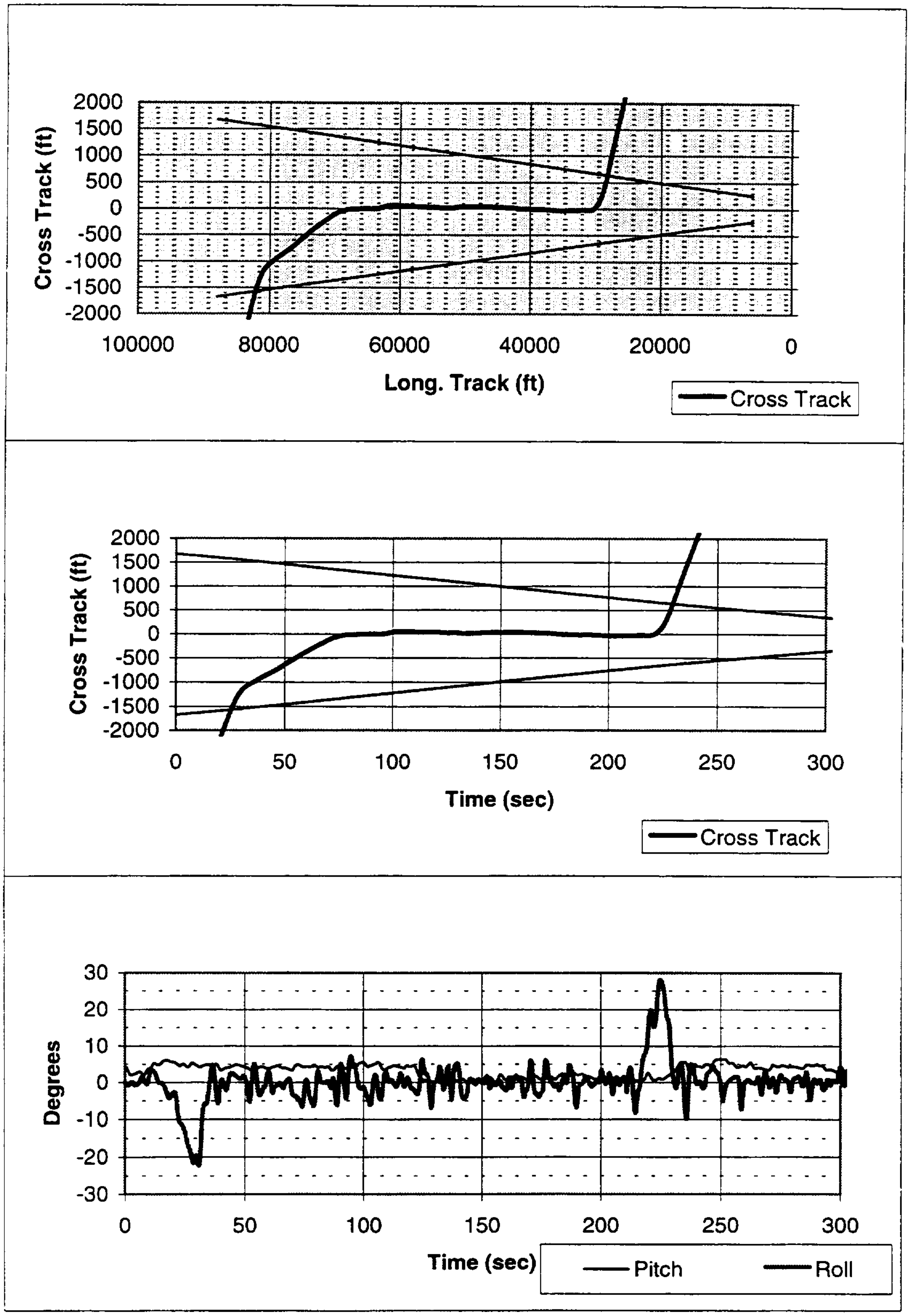


Figure C-5A 30 Degree Heading Blunder "FB30"
(145 knot Ground Speed, 12.5 knot Wind Gusts, Fog)

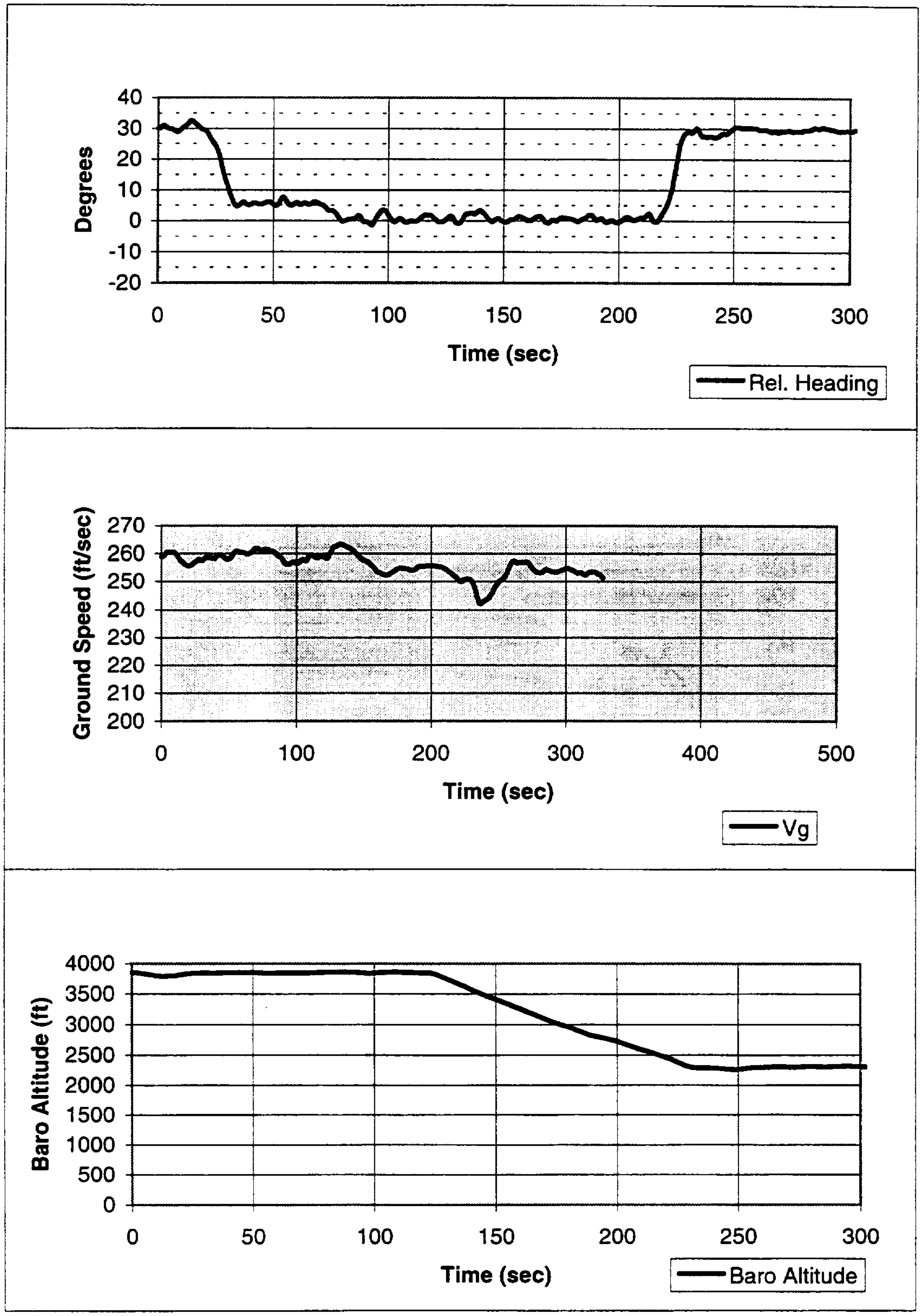


Figure C-5B 30 Degree Heading Blunder "FB30"
(145 knot Ground Speed, 12.5 knot Wind Gusts, Fog)

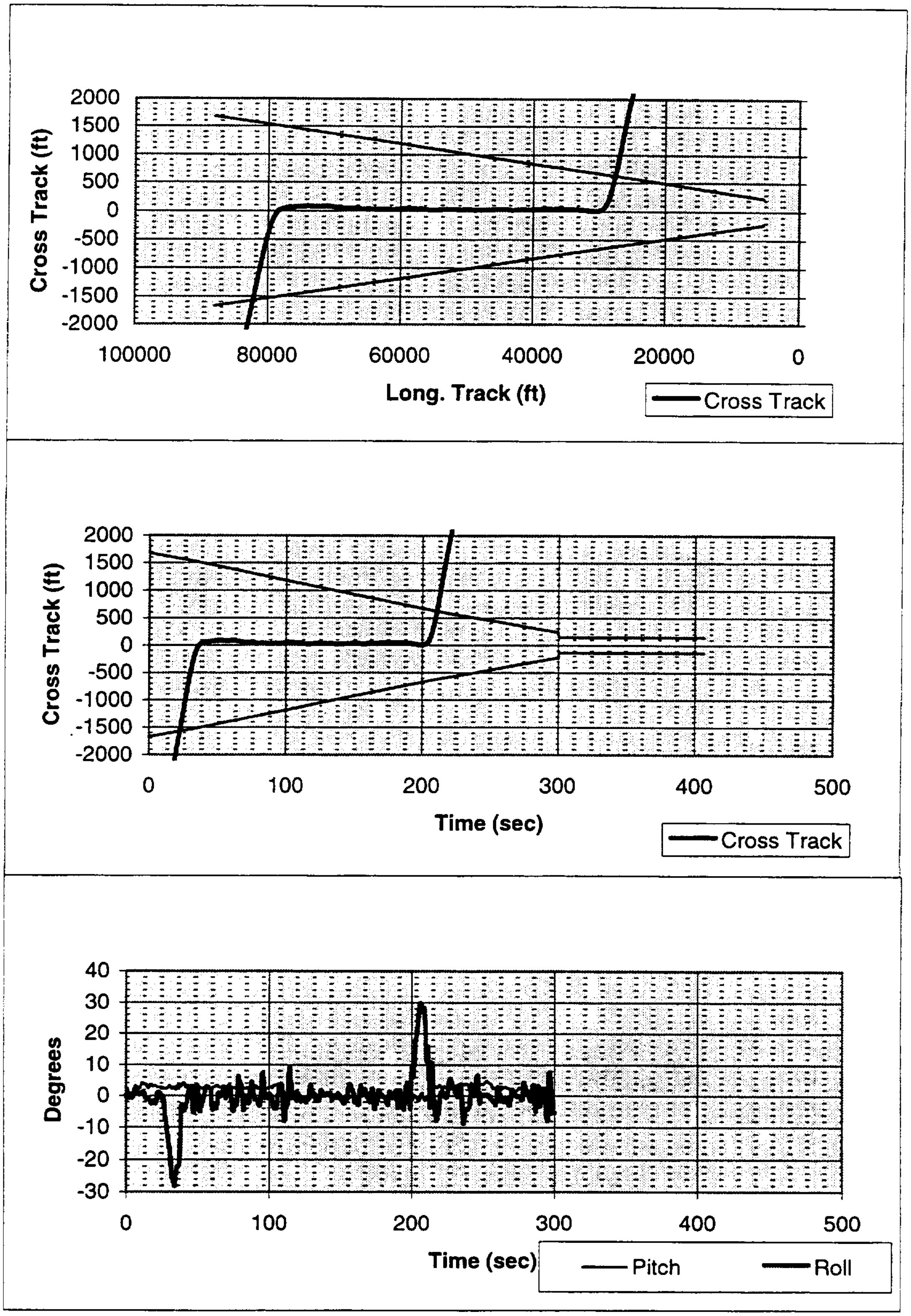


Figure C-6A 30 Degree Heading Blunder "FB30"
(160 knot Ground Speed, 12.5 knot Wind Gusts, Fog)

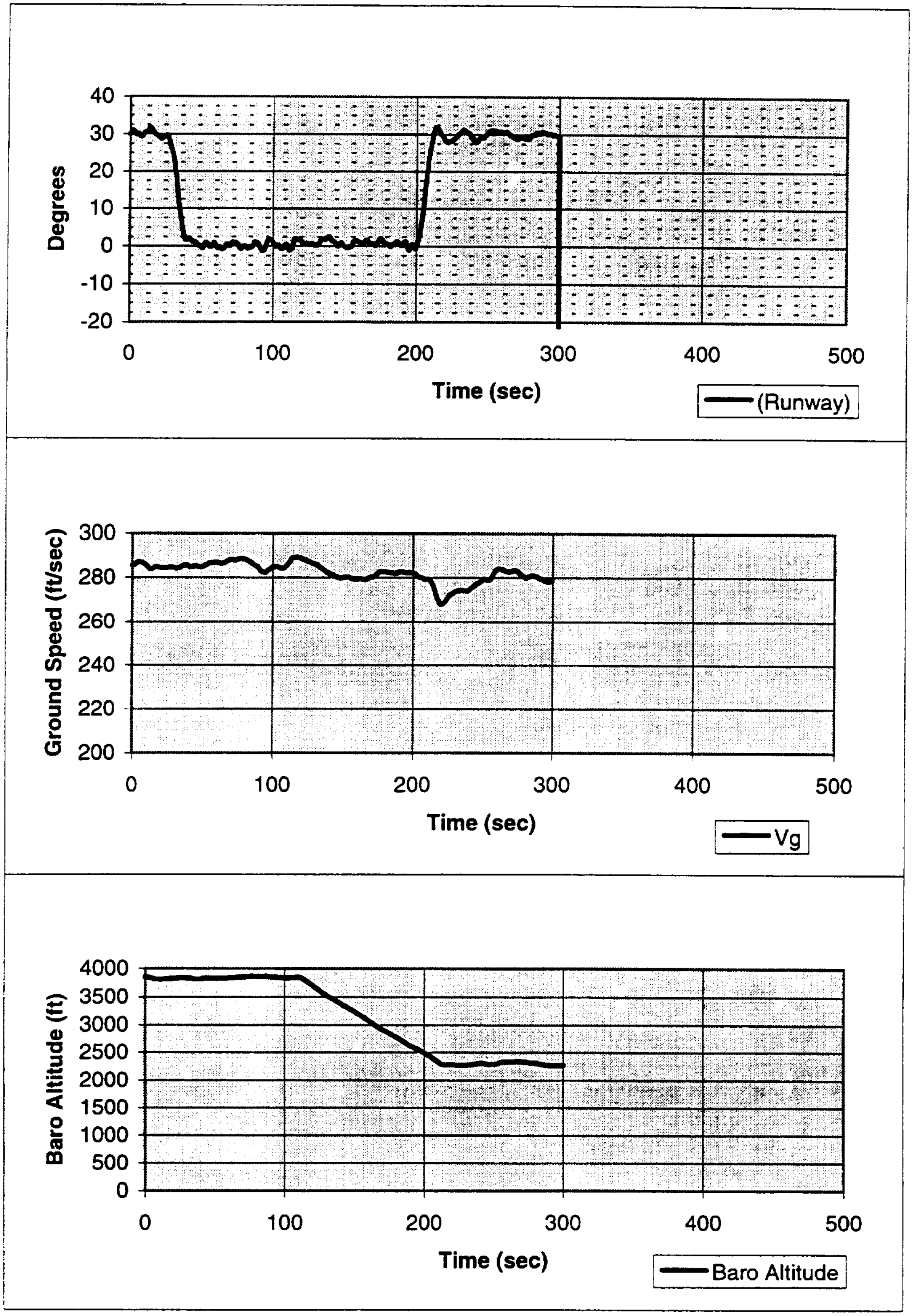


Figure C-6B 30 Degree Heading Blunder "FB30"
(160 knot Ground Speed, 12.5 knot Wind Gusts, Fog)

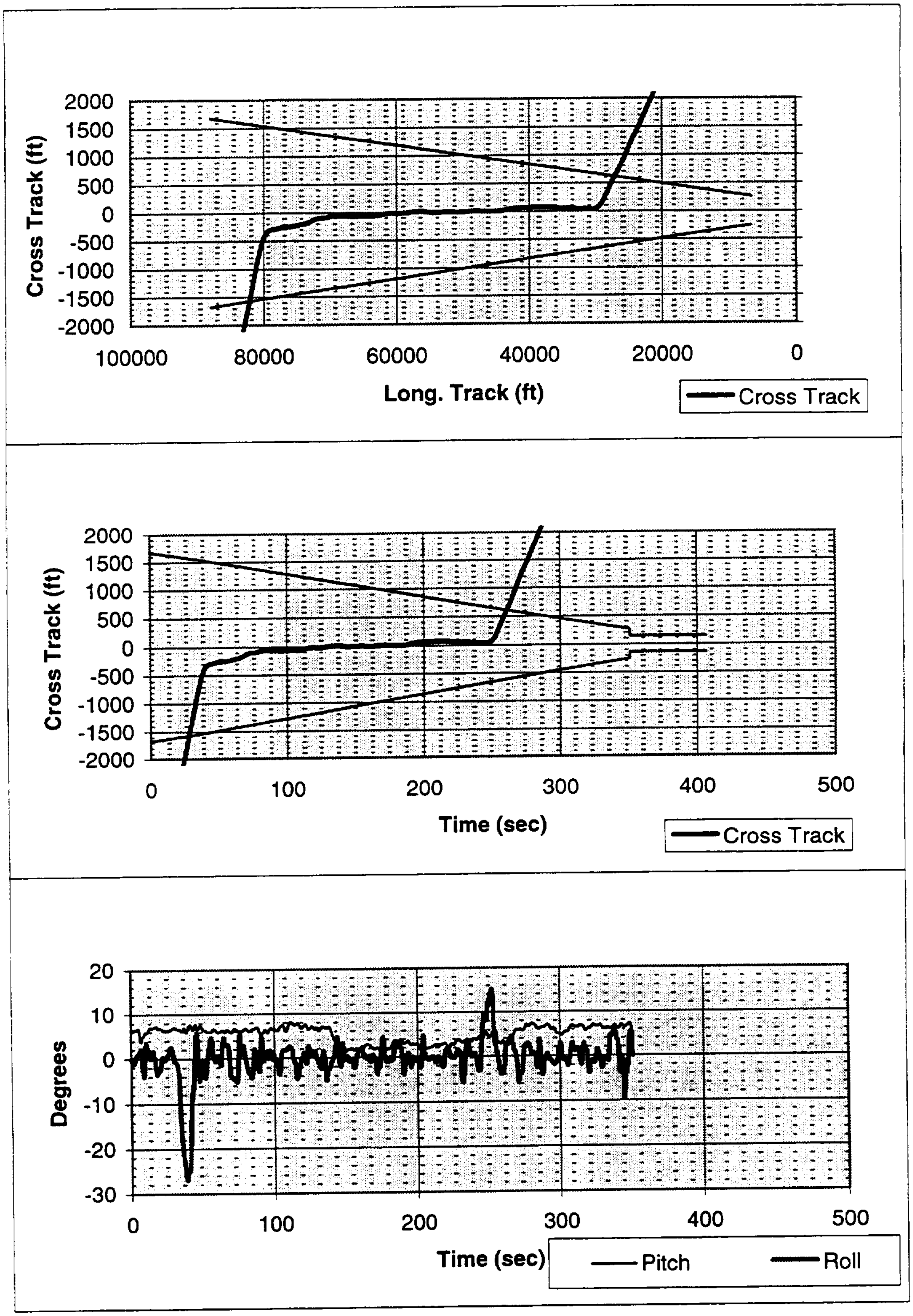


Figure C-7A 15 Degree Heading Blunder "FB15"
(130 knot Ground Speed, 12.5 knot Wind Gusts, Fog)

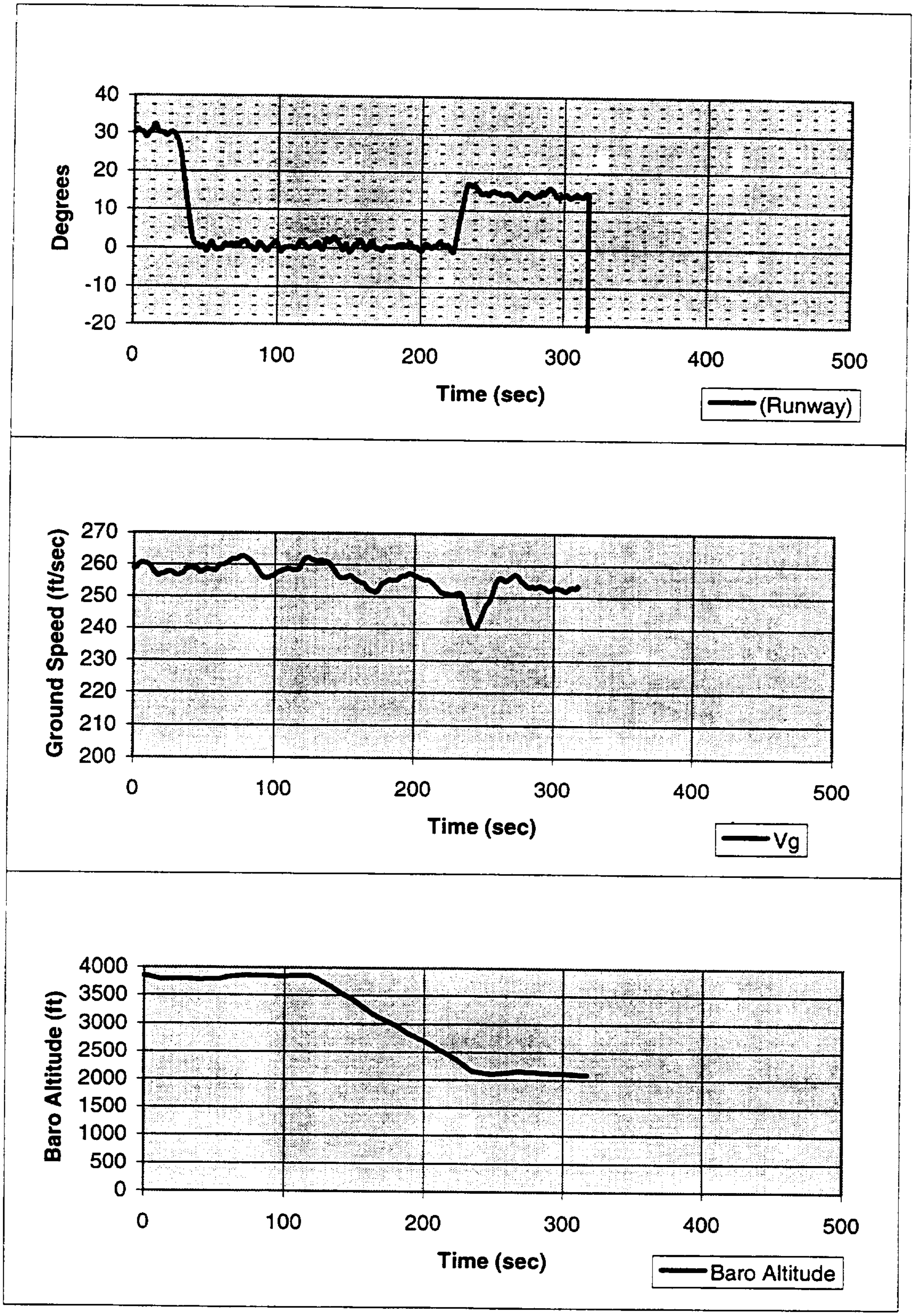


Figure C-8B 15 Degree Heading Blunder "FB15"
(145 knot Ground Speed, 12.5 knot Wind Gusts, Fog)

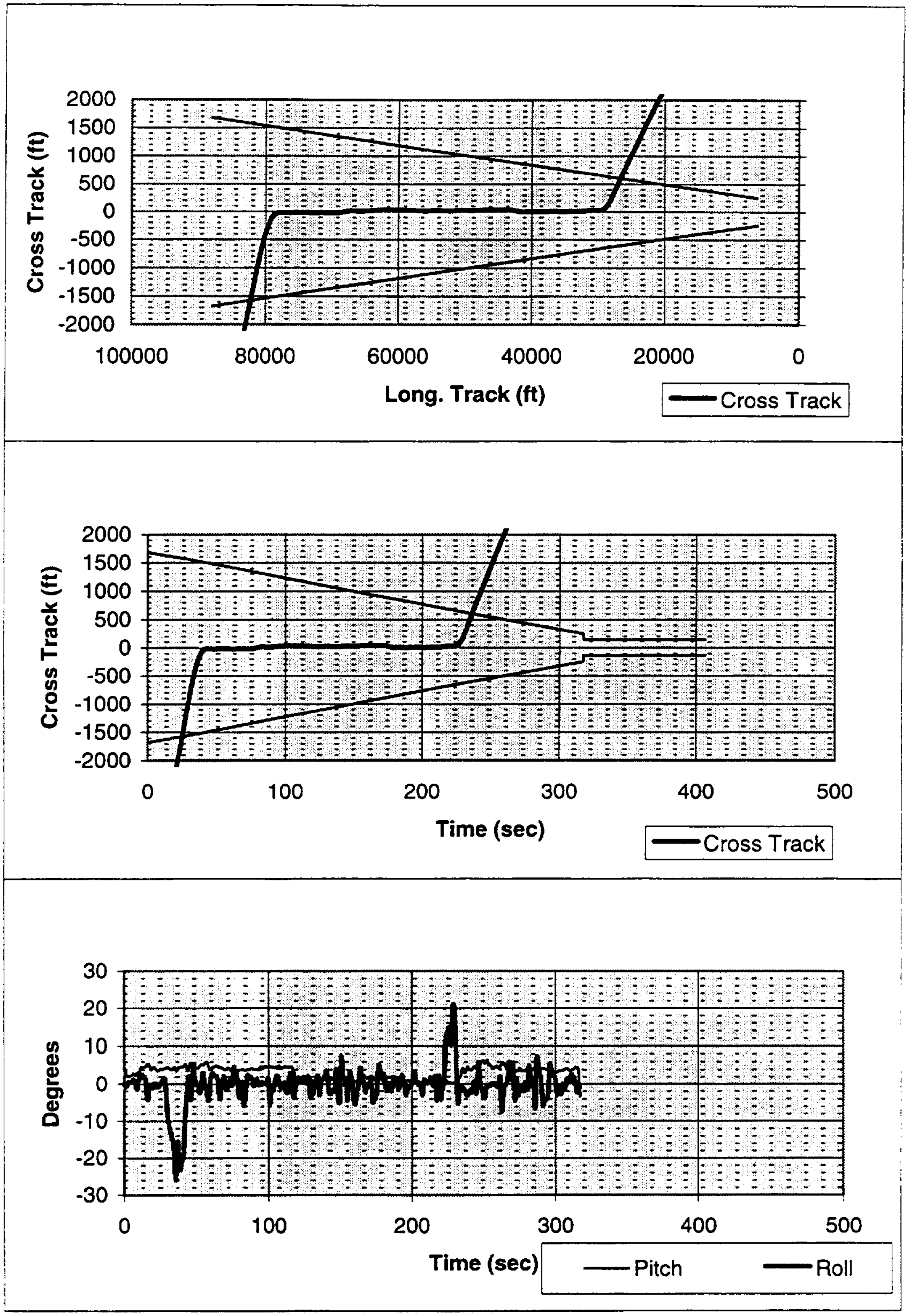


Figure C-8A 15 Degree Heading Blunder "FB15"
(145 knot Ground Speed, 12.5 knot Wind Gusts, Fog)

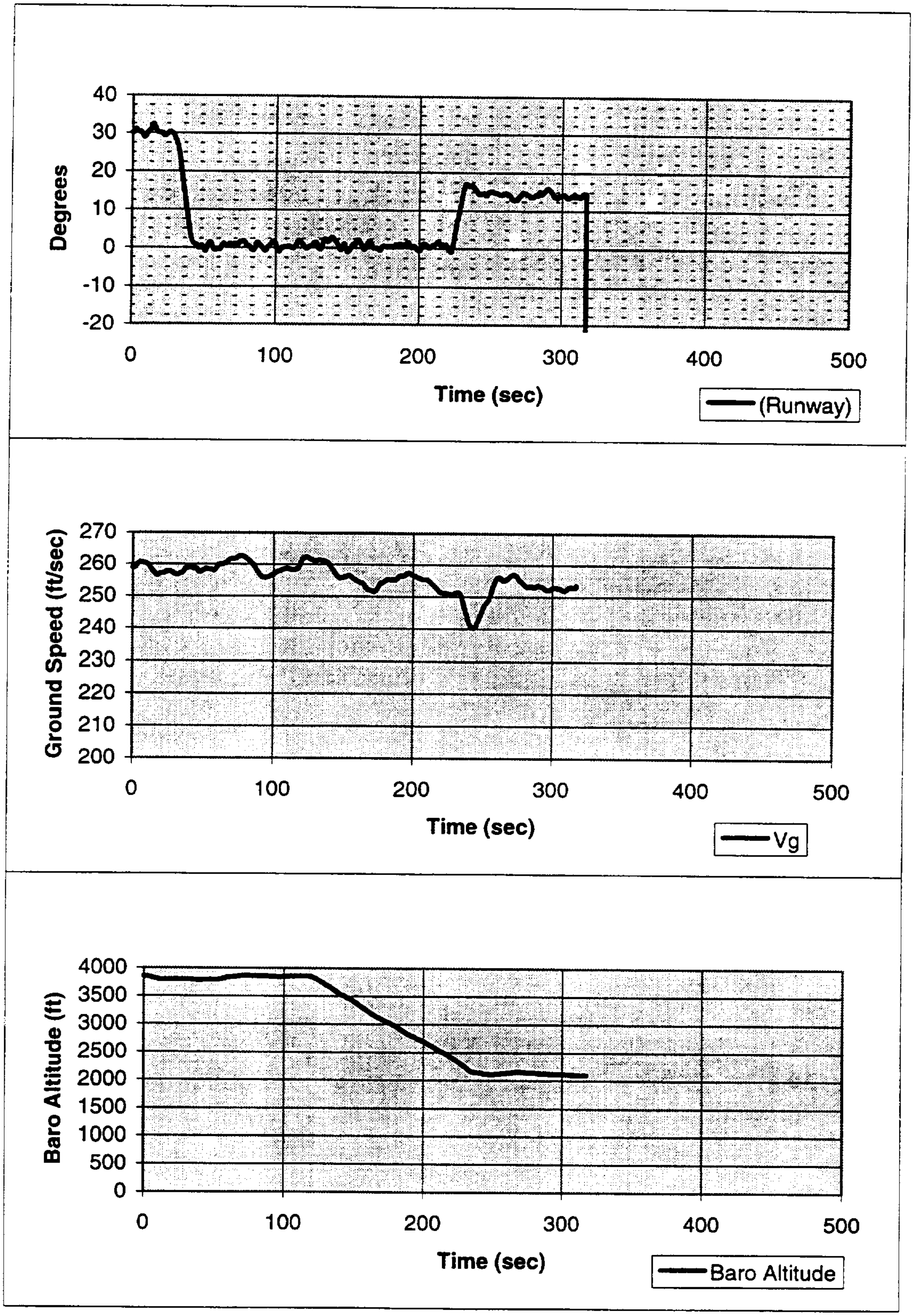


Figure C-8B 15 Degree Heading Blunder "FB15"
(145 knot Ground Speed, 12.5 knot Wind Gusts, Fog)

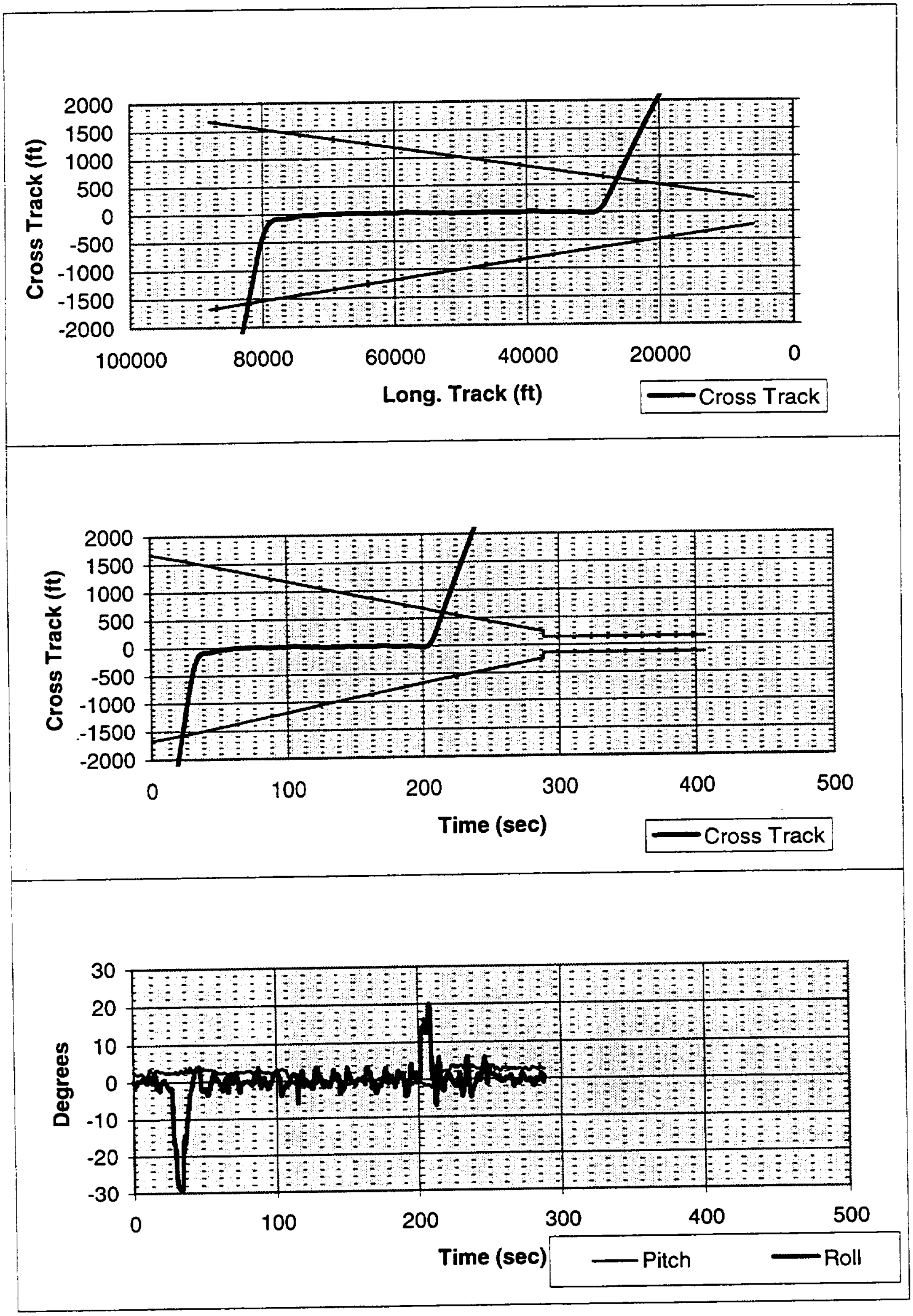


Figure C-9A 15 Degree Heading Blunder "FB15"
(160 knot Ground Speed, 12.5 knot Wind Gusts, Fog)

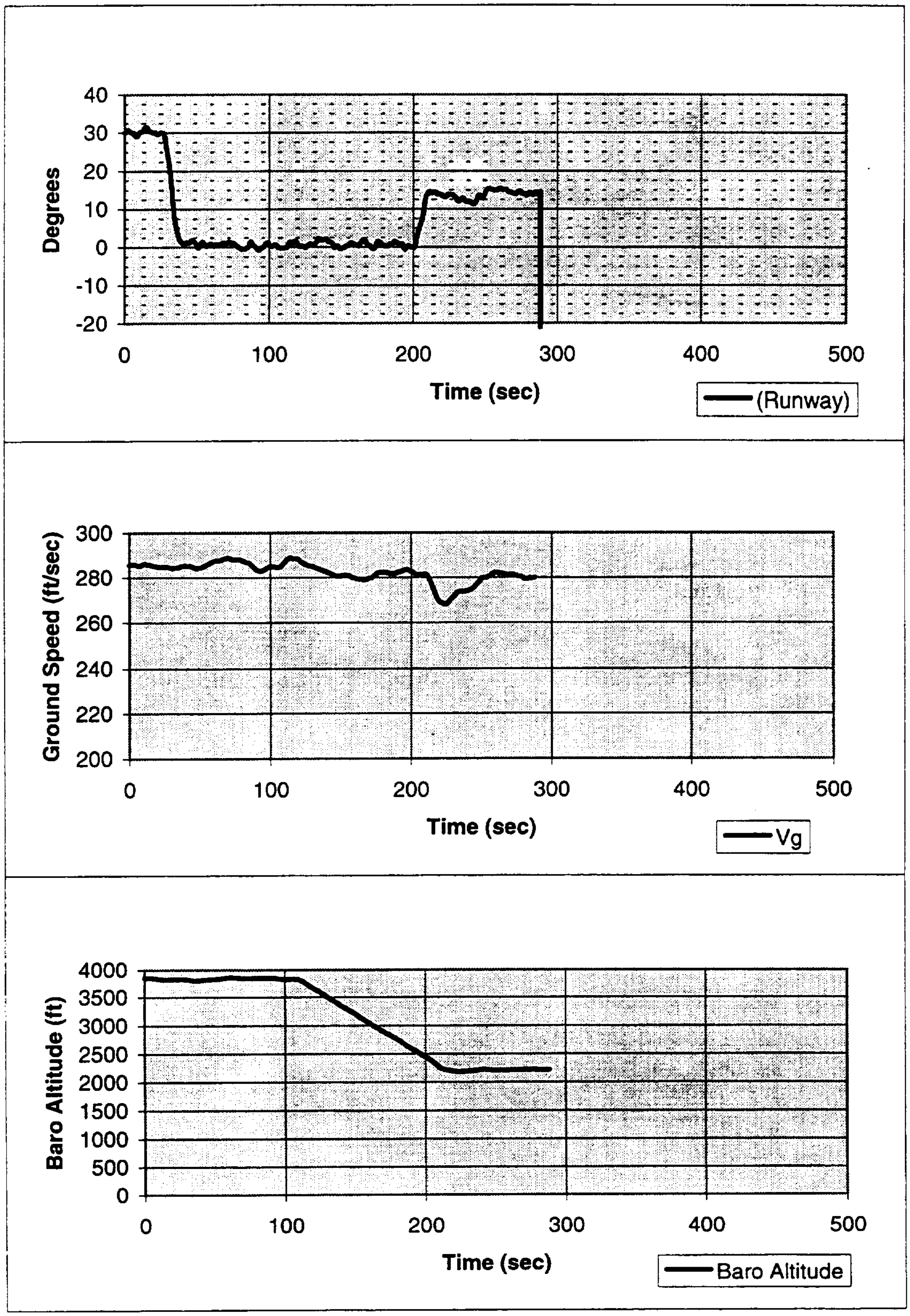


Figure C-9B 15 Degree Heading Blunder "FB15"
(160 knot Ground Speed, 12.5 knot Wind Gusts, Fog)

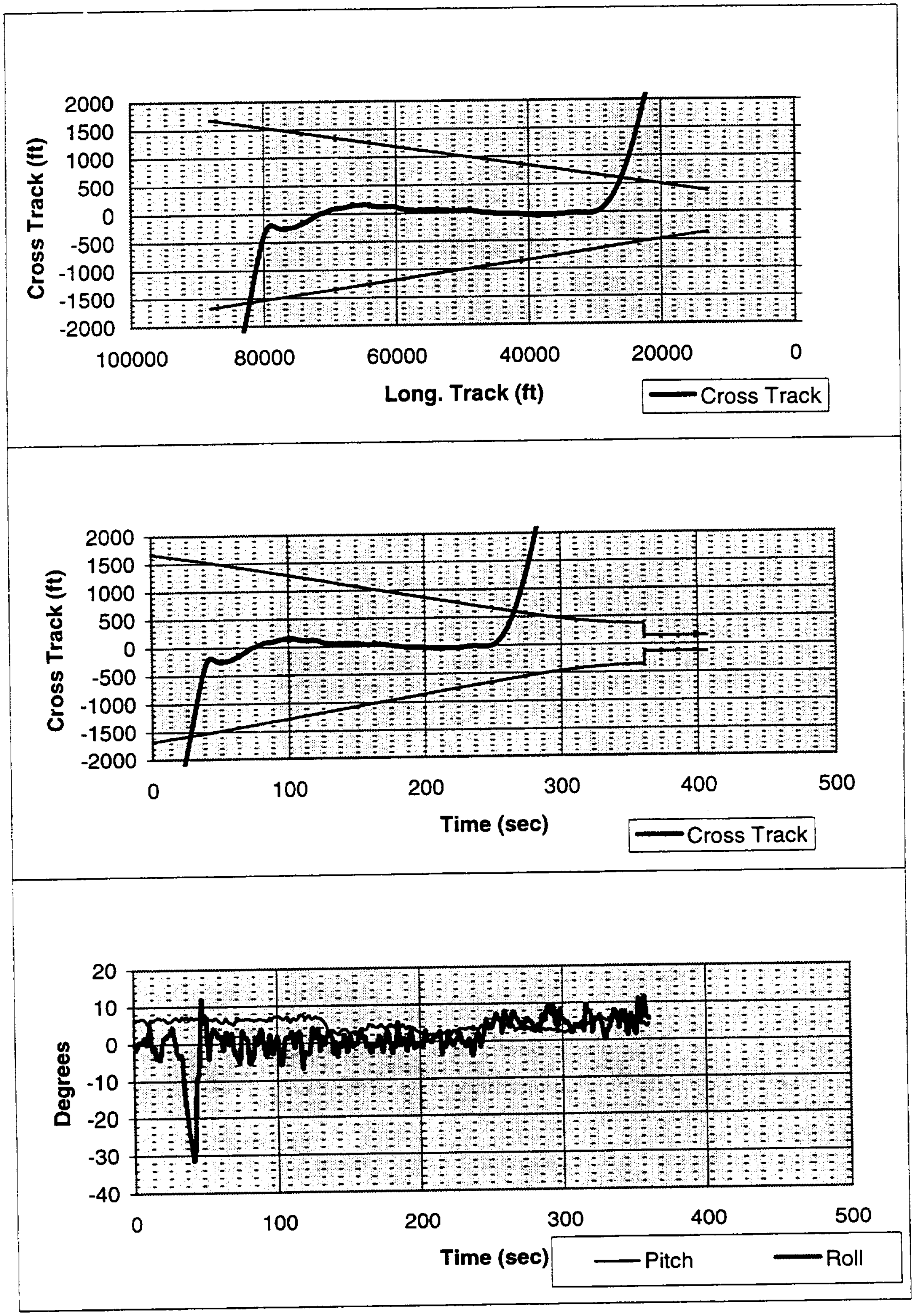


Figure C-10A Constant 5 Degree Bank Angle Blunder "FSB5"
(130 knot Ground Speed, 12.5 knot Wind Gusts, Fog)

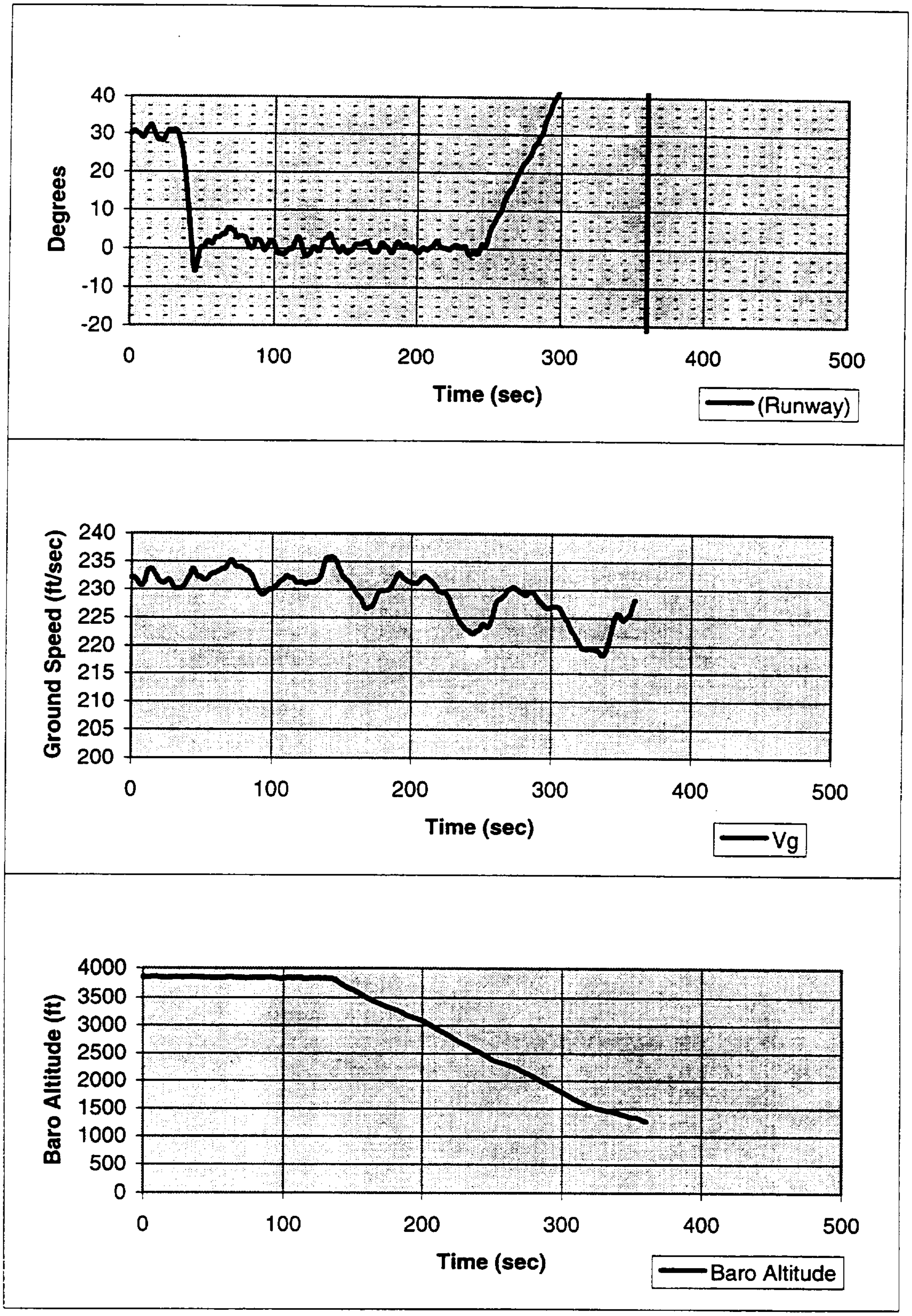


Figure C-10B Constant 5 Degree Bank Angle Blunder "FSB5"
(130 knot Ground Speed, 12.5 knot Wind Gusts, Fog)

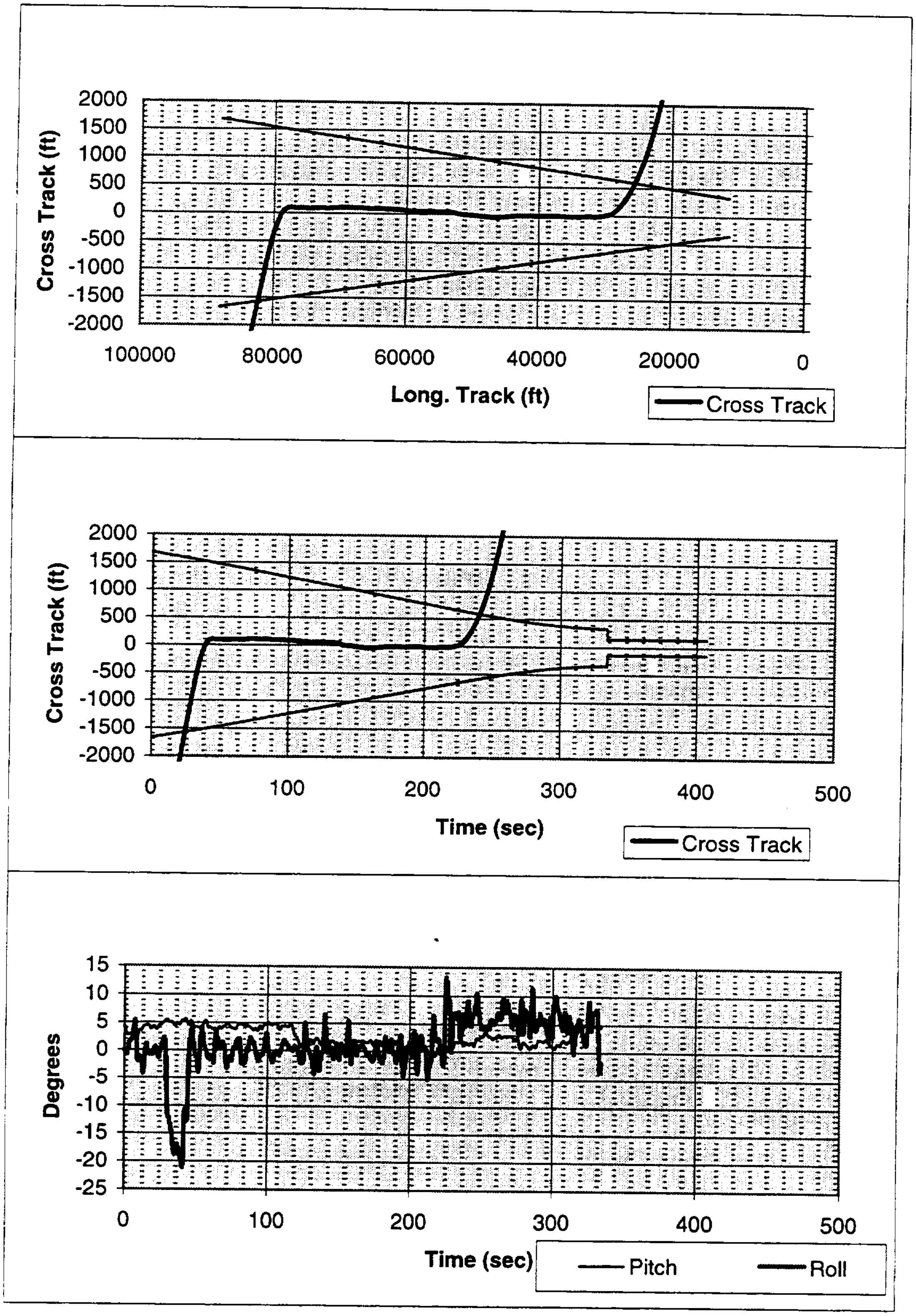


Figure C-11A Constant 5 Degree Bank Angle Blunder "FSB5"
(145 knot Ground Speed, 12.5 knot Wind Gusts, Fog)

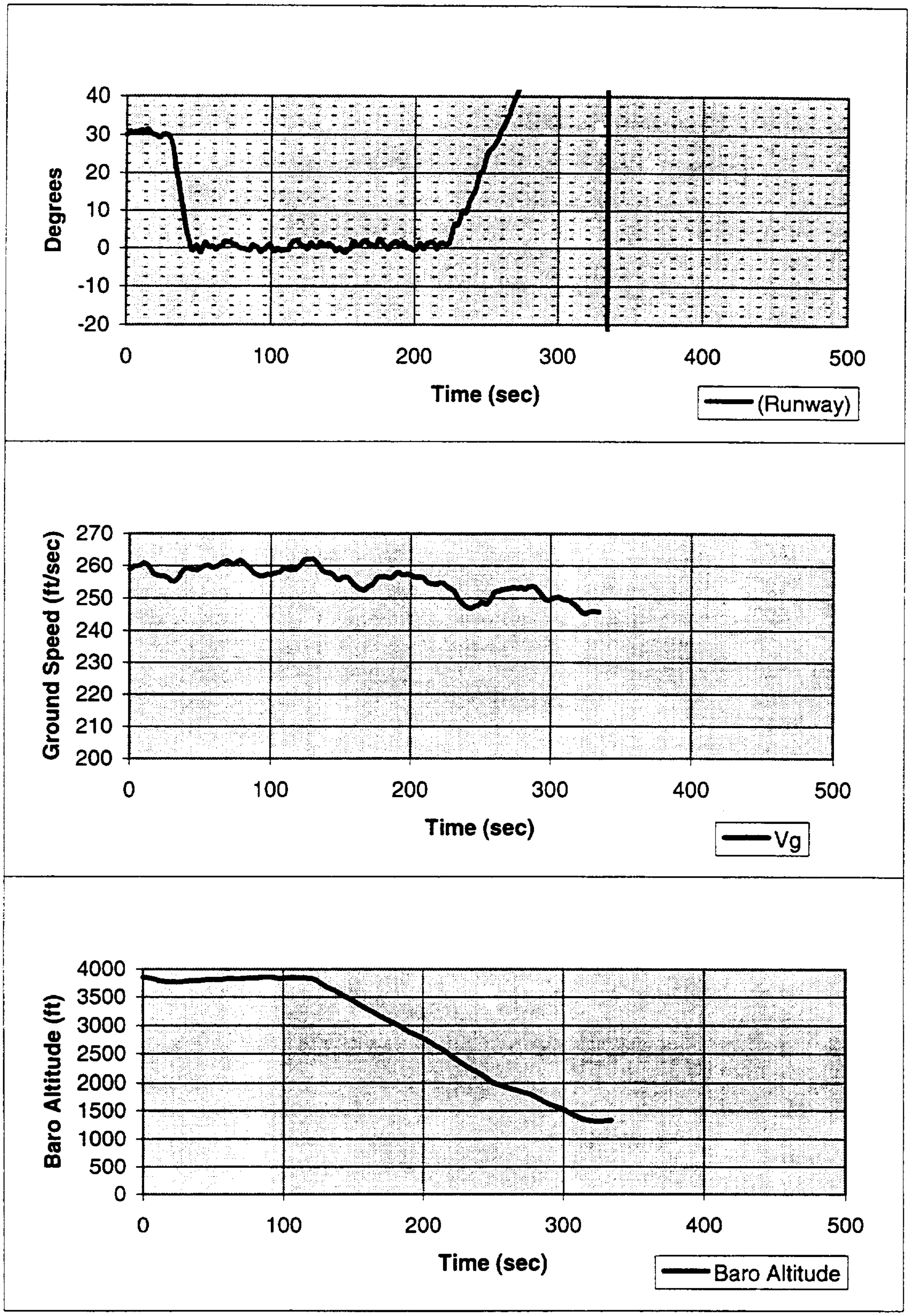


Figure C-11B Constant 5 Degree Bank Angle Blunder "FSB5"
(145 knot Ground Speed, 12.5 knot Wind Gusts, Fog)

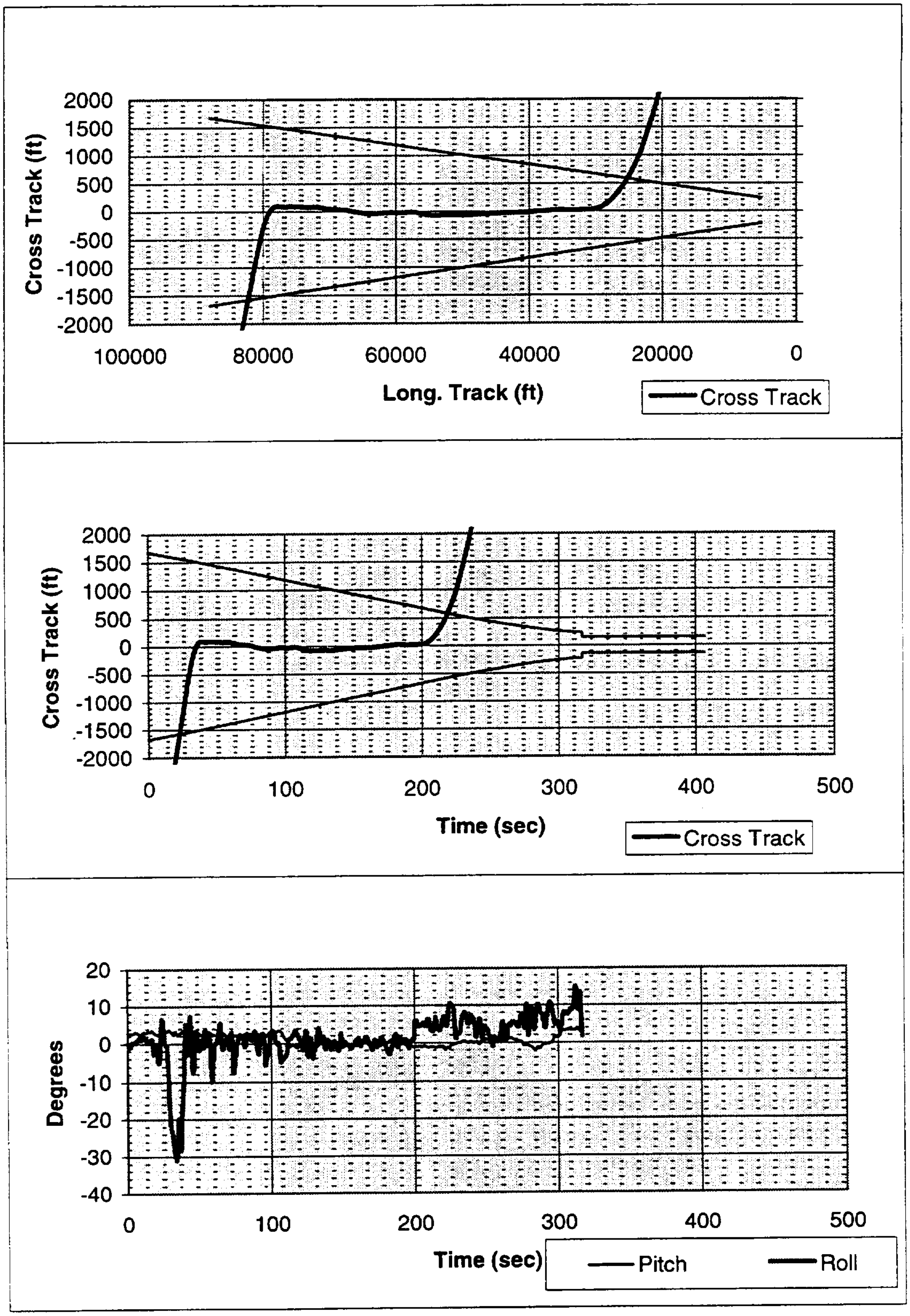


Figure C-12A Constant 5 Degree Bank Angle Blunder "FSB5"
(160 knot Ground Speed, 12.5 knot Wind Gusts, Fog)

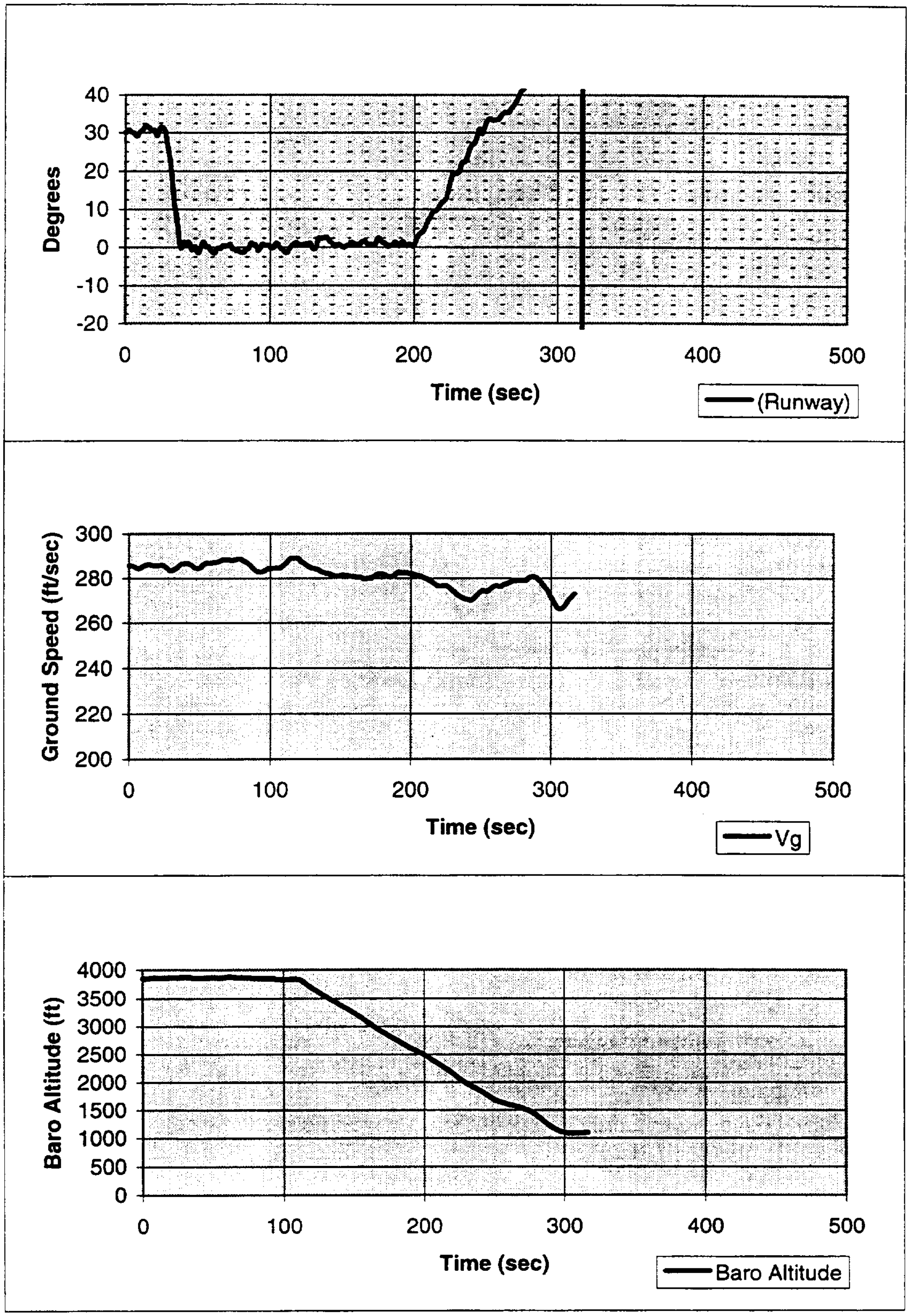


Figure C-12B Constant 5 Degree Bank Angle Blunder "FSB5"
(160 knot Ground Speed, 12.5 knot Wind Gusts, Fog)

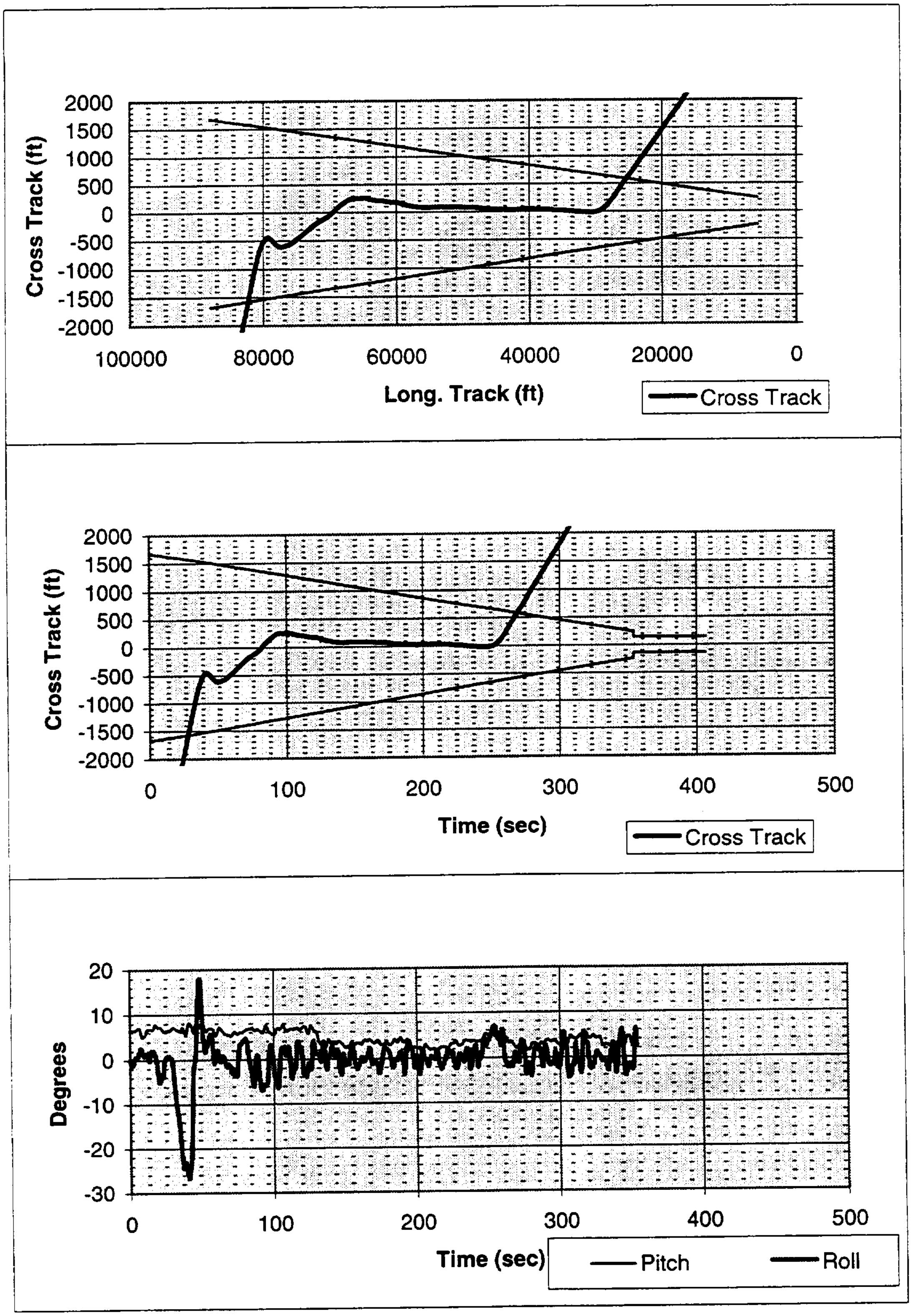


Figure C-13A Slow 10 Degree Heading Change Blunder "FSLO"
(130 knot Ground Speed, 12.5 knot Wind Gusts, Fog)

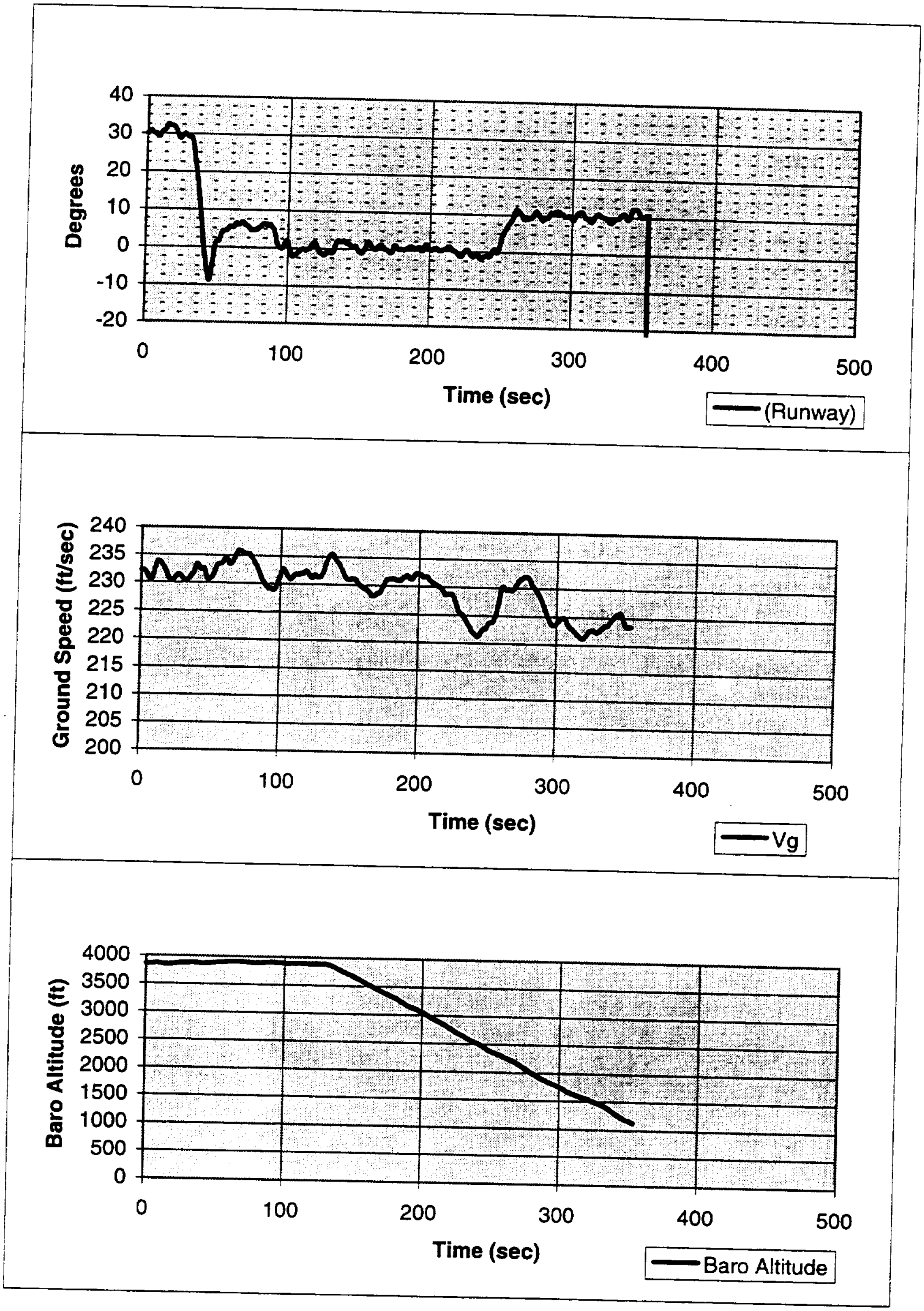


Figure C-13B Slow 10 Degree Heading Change Blunder "FSLO"
(130 knot Ground Speed, 12.5 knot Wind Gusts, Fog)

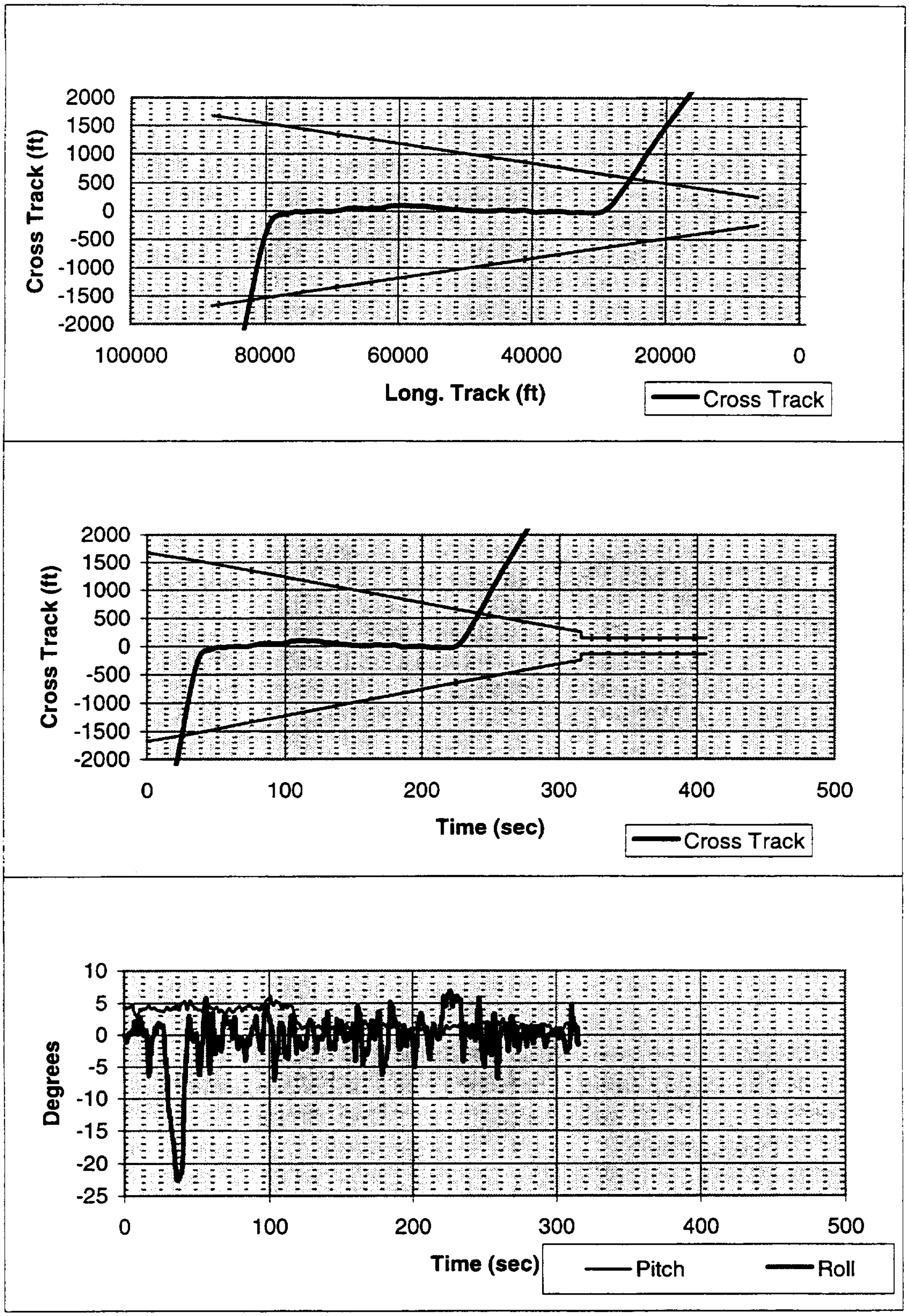


Figure C-14A Slow 10 Degree Heading Change Blunder - "FSLO"
(145 knot Ground Speed, 12.5 knot Wind Gusts, Fog)

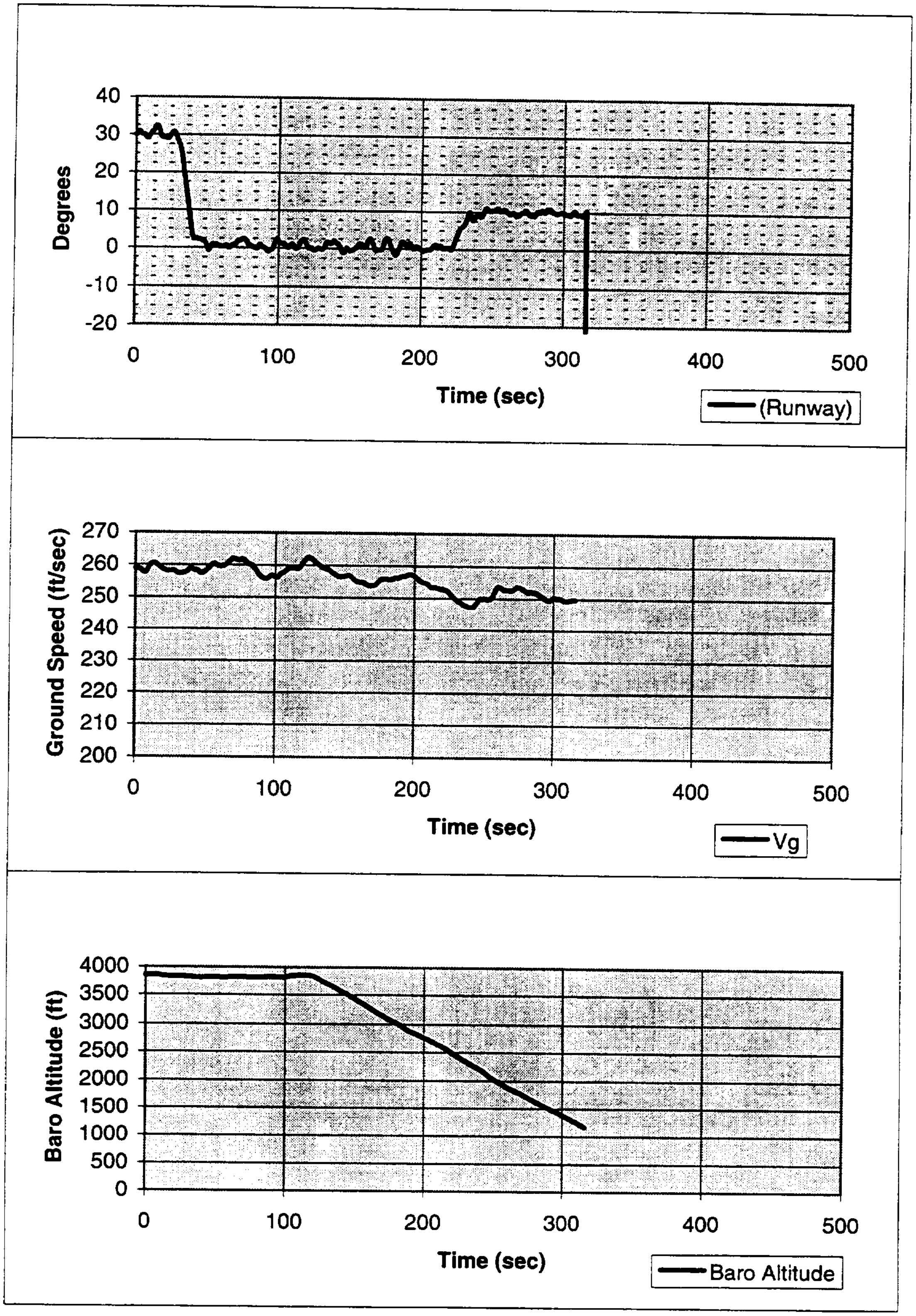


Figure C-14B Slow 10 Degree Heading Change Blunder - "FSLO"
(145 knot Ground Speed, 12.5 knot Wind Gusts, Fog)

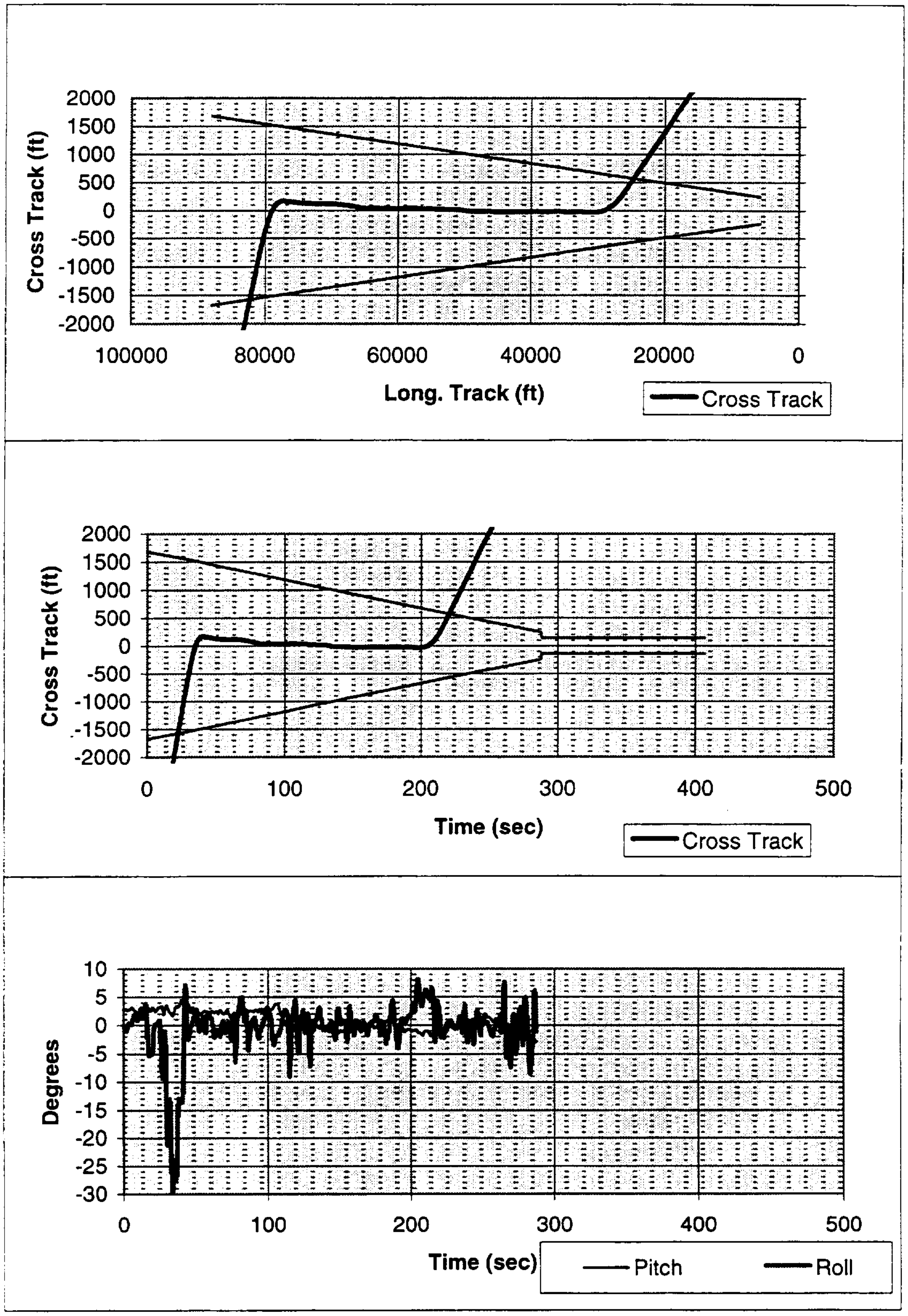


Figure C-15A Slow 10 Degree Heading Change Blunder "FSLO"
(160 knot Ground Speed, 12.5 knot Wind Gusts, Fog)

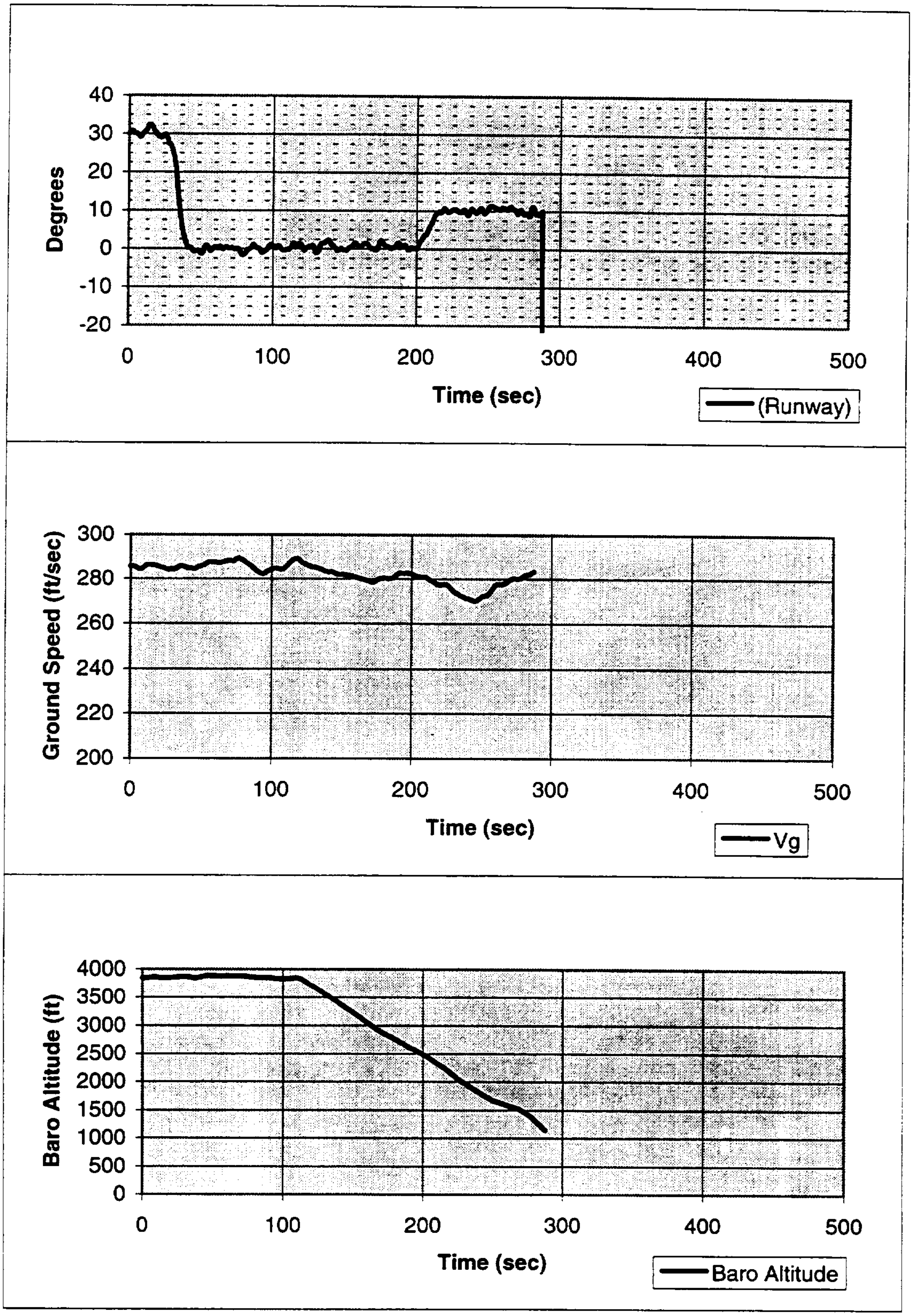


Figure C-15B Slow 10 Degree Heading Change Blunder "FSLO"
(160 knot Ground Speed, 12.5 knot Wind Gusts, Fog)

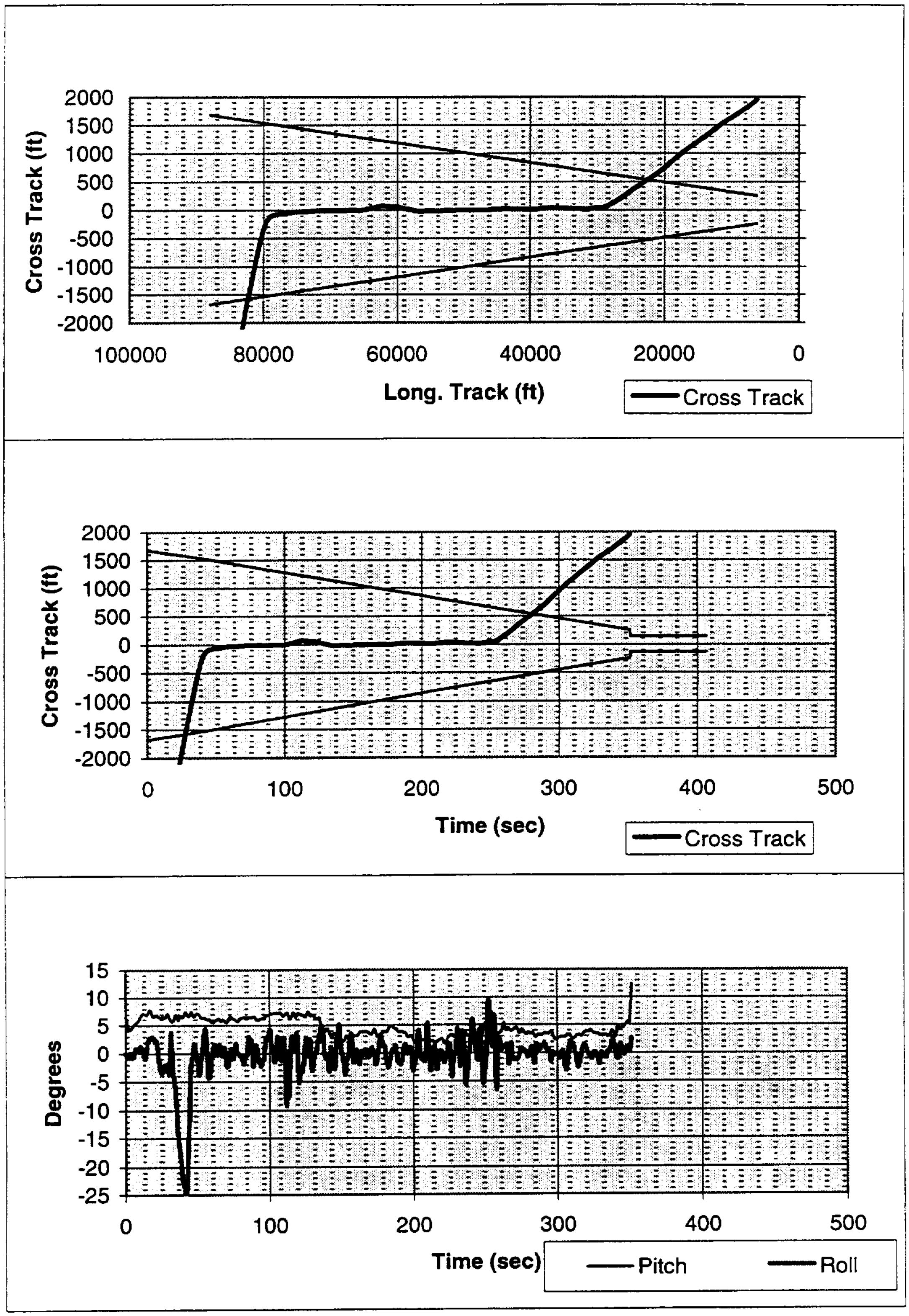


Figure C-16A Slow 5 Degree Heading Change Blunder "FSH5"
(130 knot Ground Speed, 12.5 knot Wind Gusts, Fog)

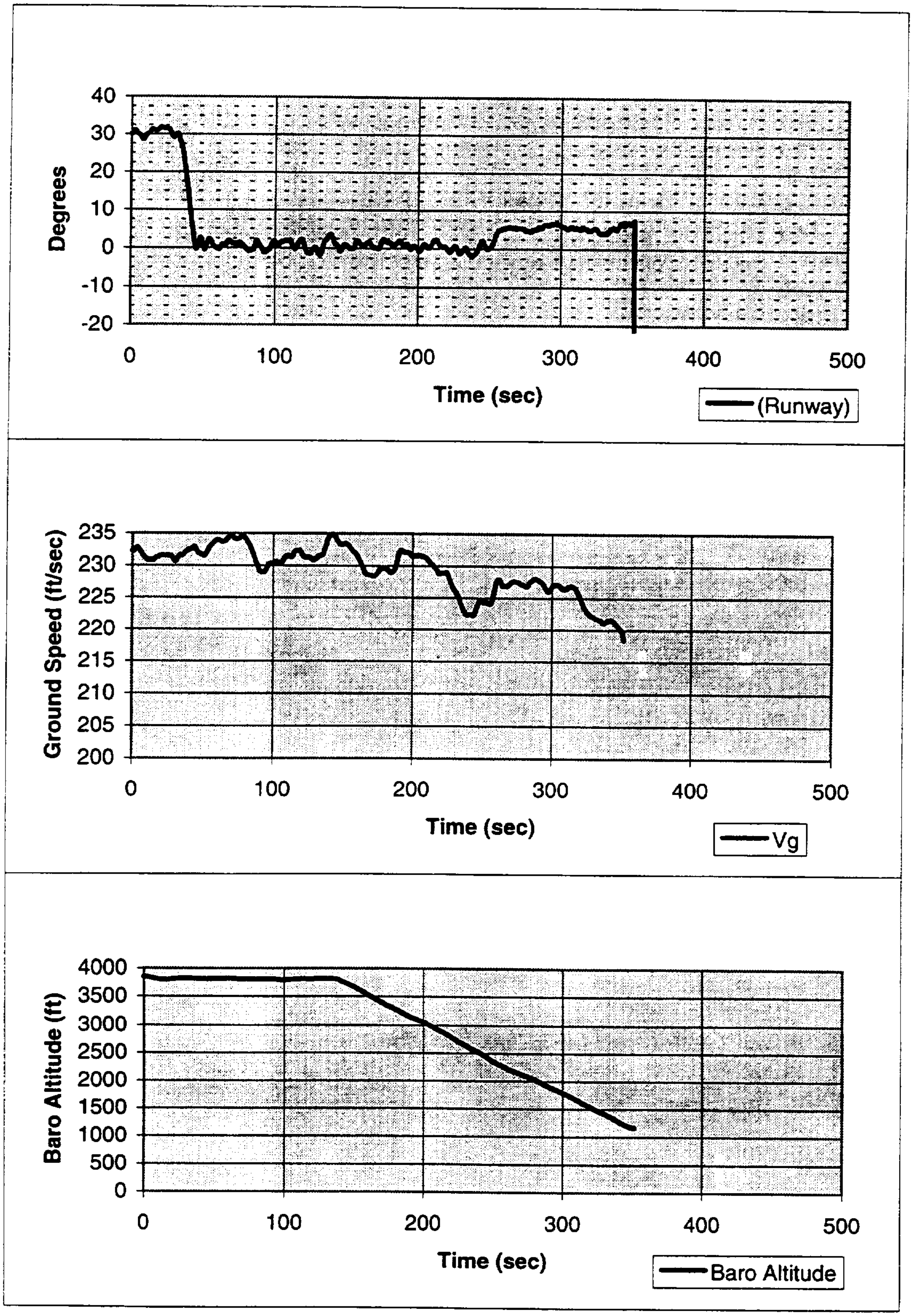


Figure C-16B Slow 5 Degree Heading Change Blunder "FSH5"
(130 knot Ground Speed, 12.5 knot Wind Gusts, Fog)

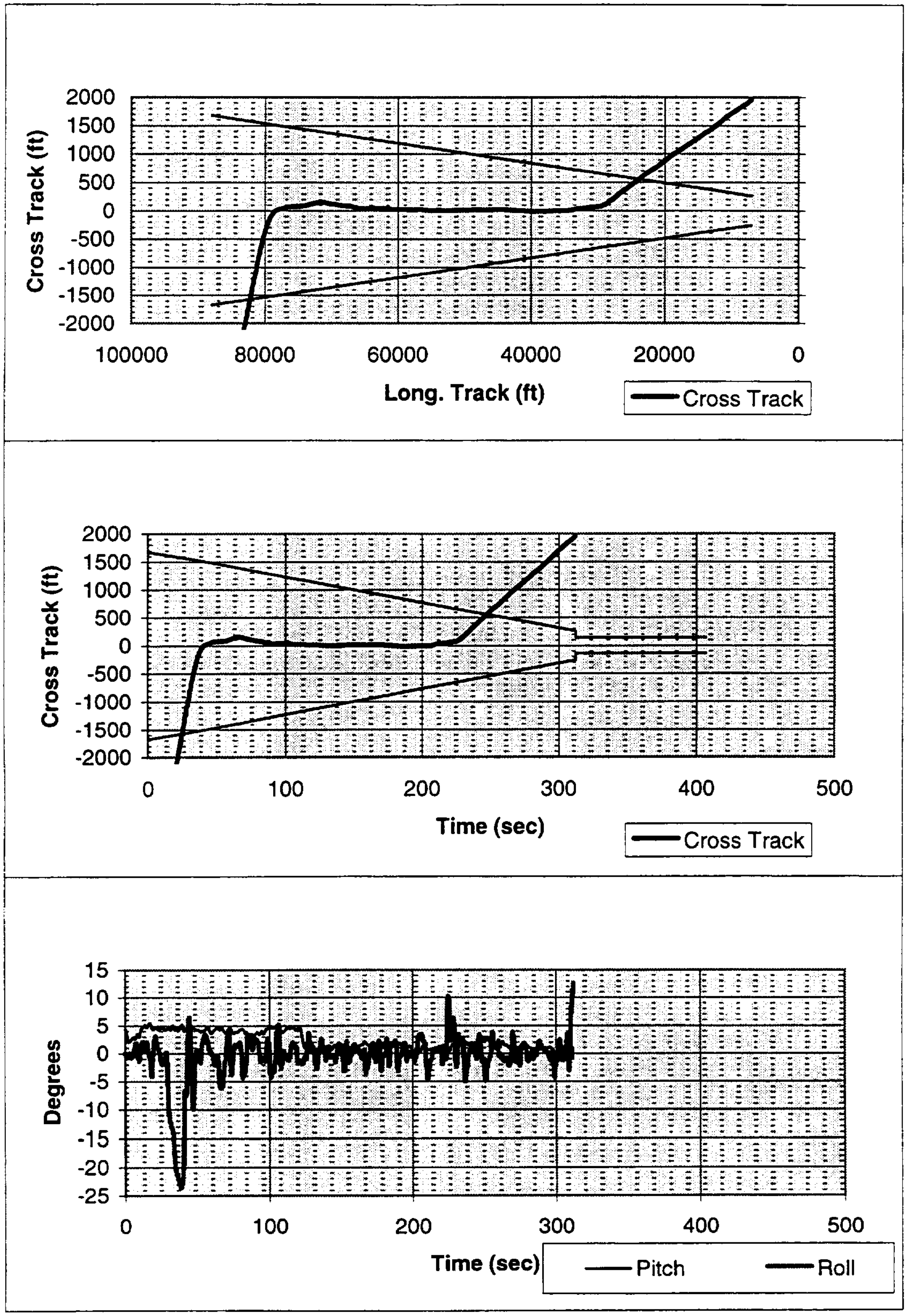


Figure C-17A Slow 5 Degree Heading Change Blunder "FSH5"
(145 knot Ground Speed, 12.5 knot Wind Gusts, Fog)

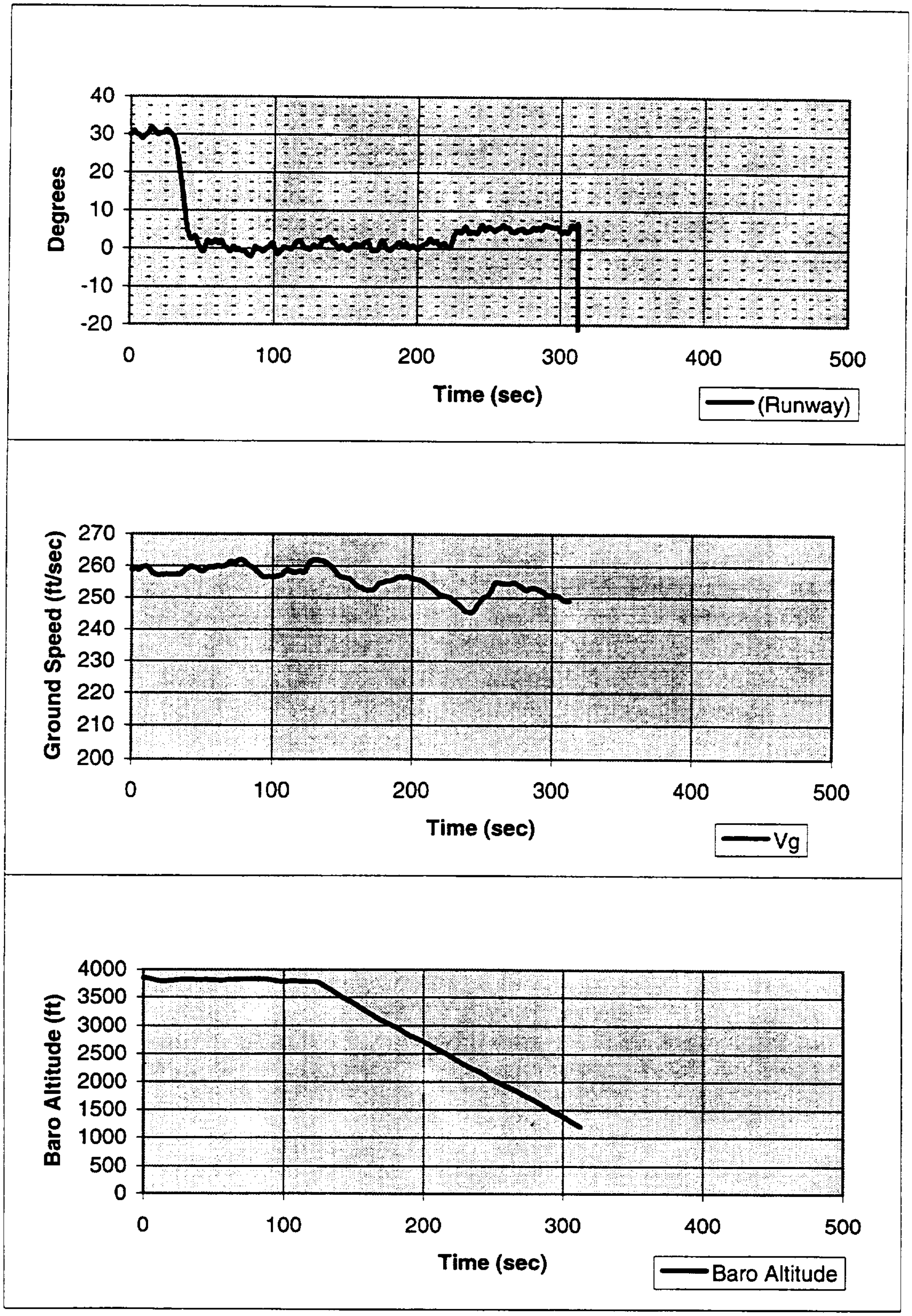


Figure C-17B Slow 5 Degree Heading Change Blunder "FSH5"
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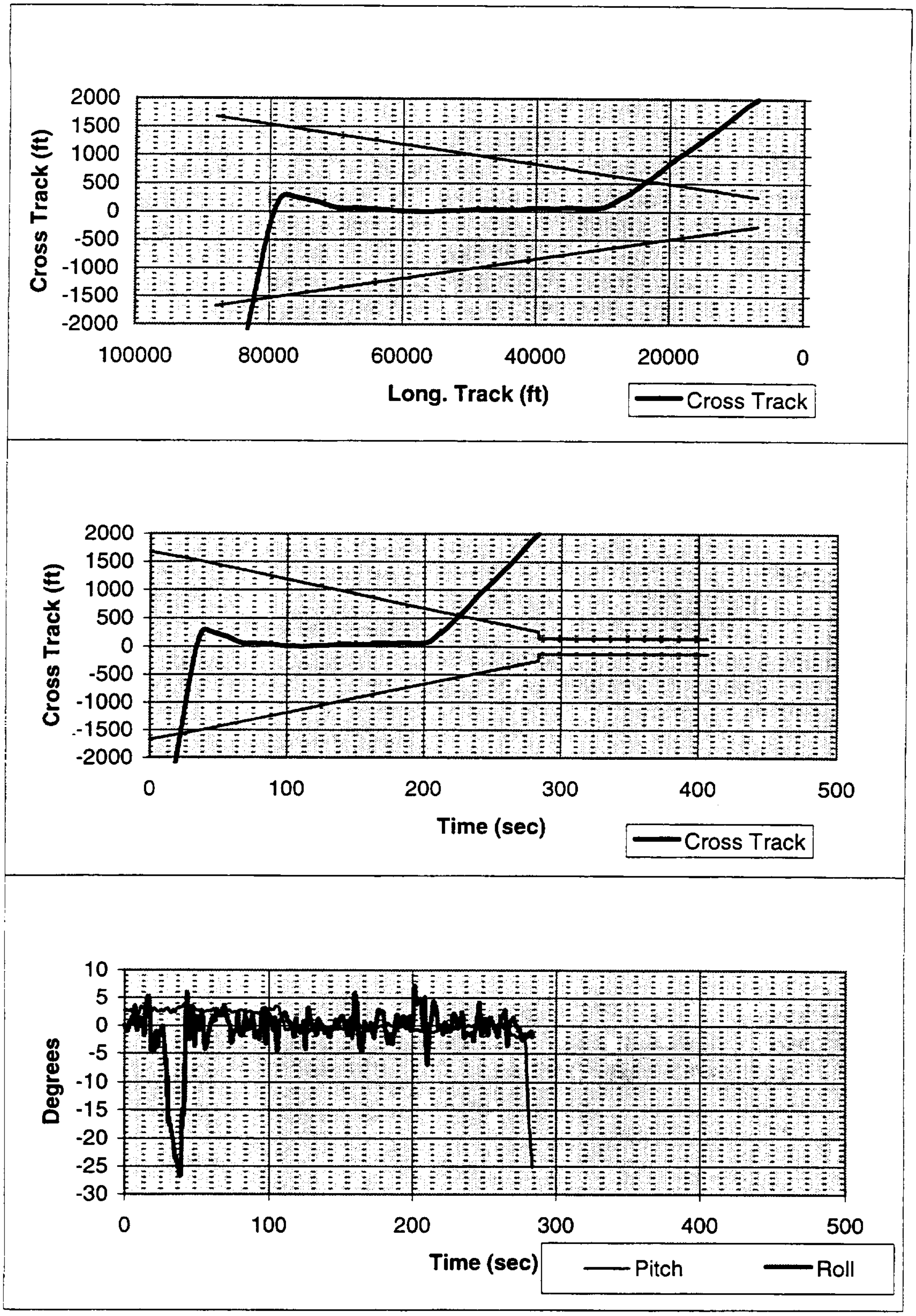

Figure C-18A Slow 5 Degree Heading Change Blunder "FSH5"
(160 knot Ground Speed, 12.5 knot Wind Gusts, Fog)

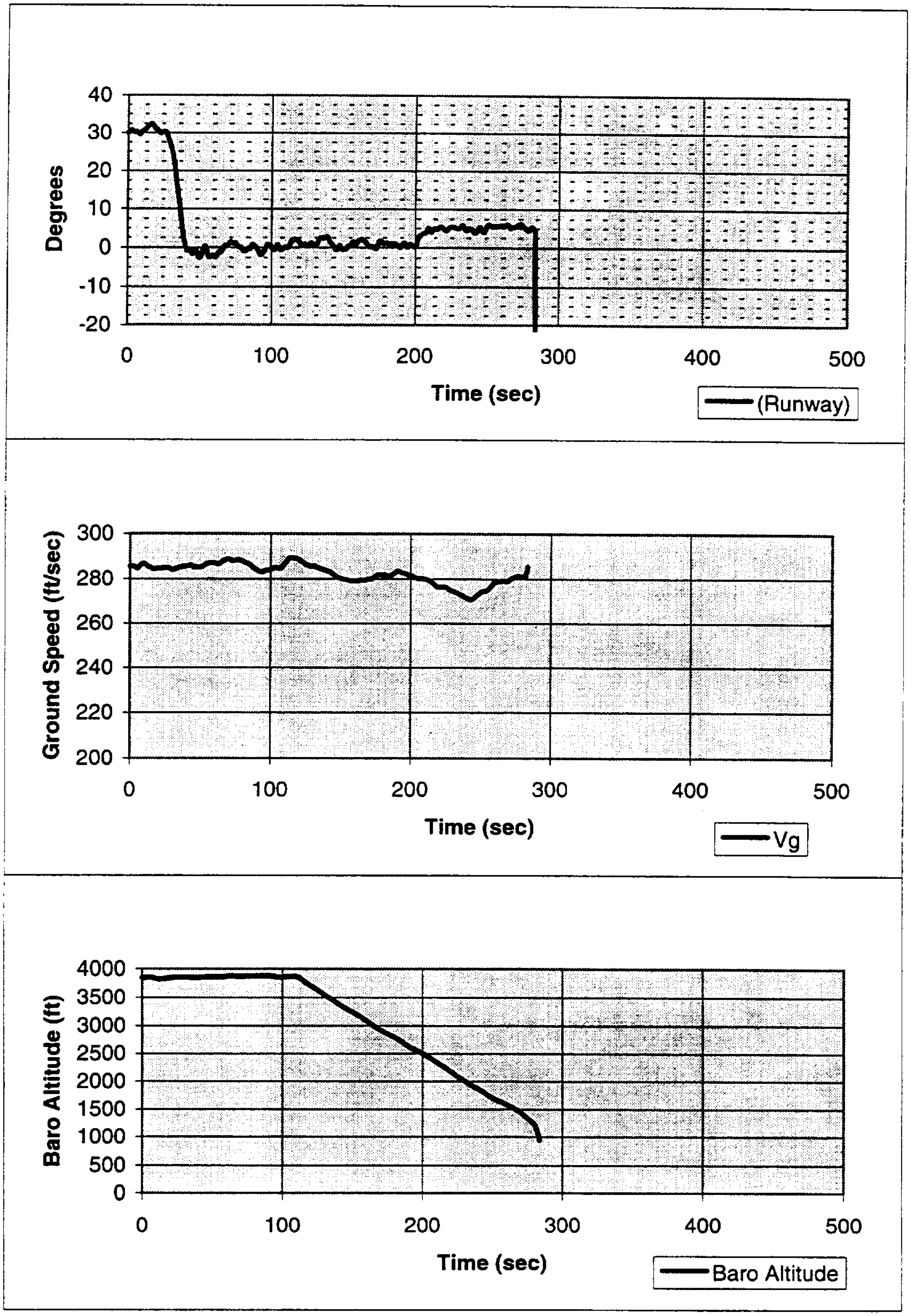

Figure C-18B Slow 5 Degree Heading Change Blunder "FSH5"
(160 knot Ground Speed, 12.5 knot Wind Gusts, Fog)

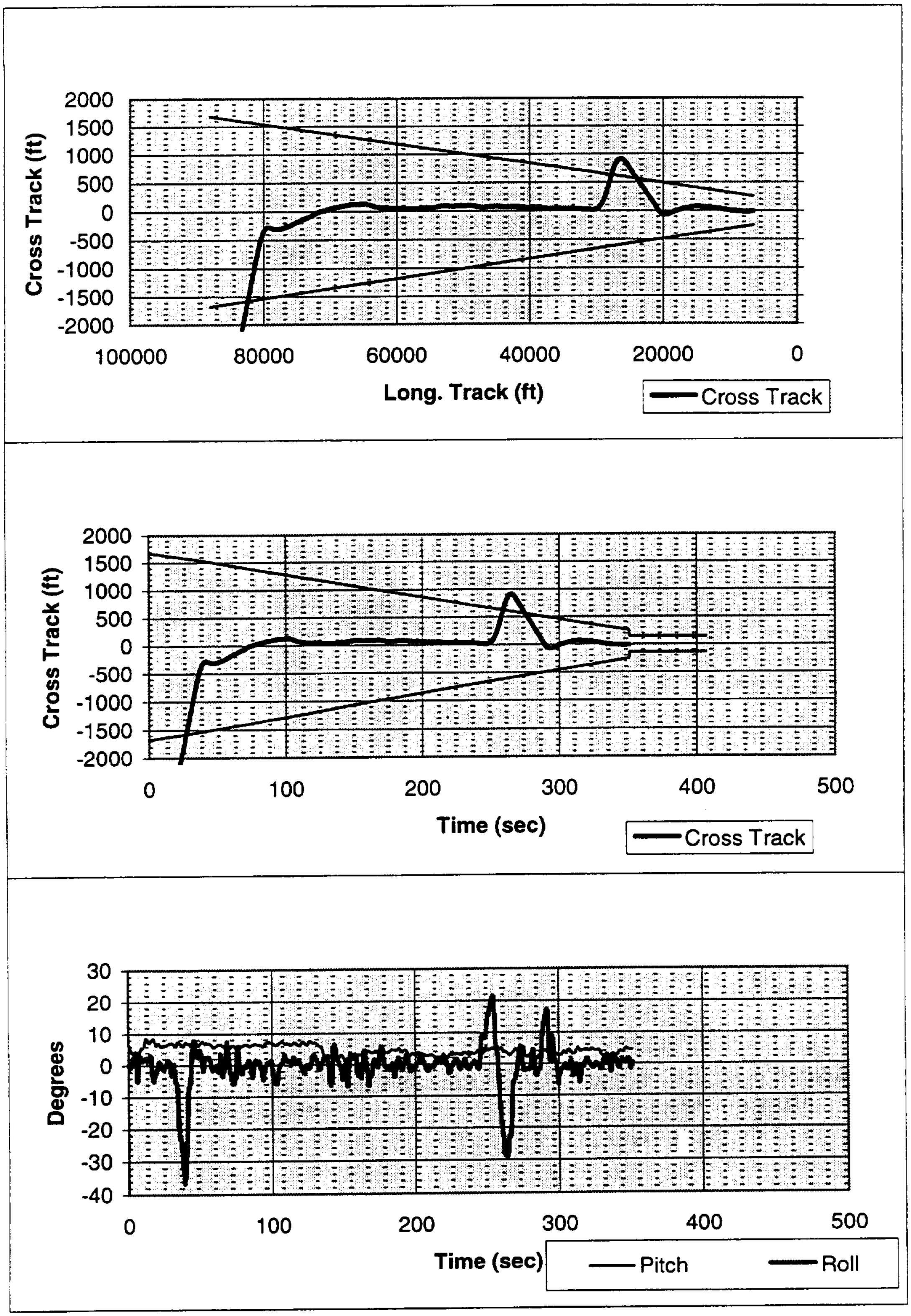

Figure C-19A Fake Blunder Toward Evader Runway "FFAK"
(130 knot Ground Speed, 12.5 knot Wind Gusts, Fog)

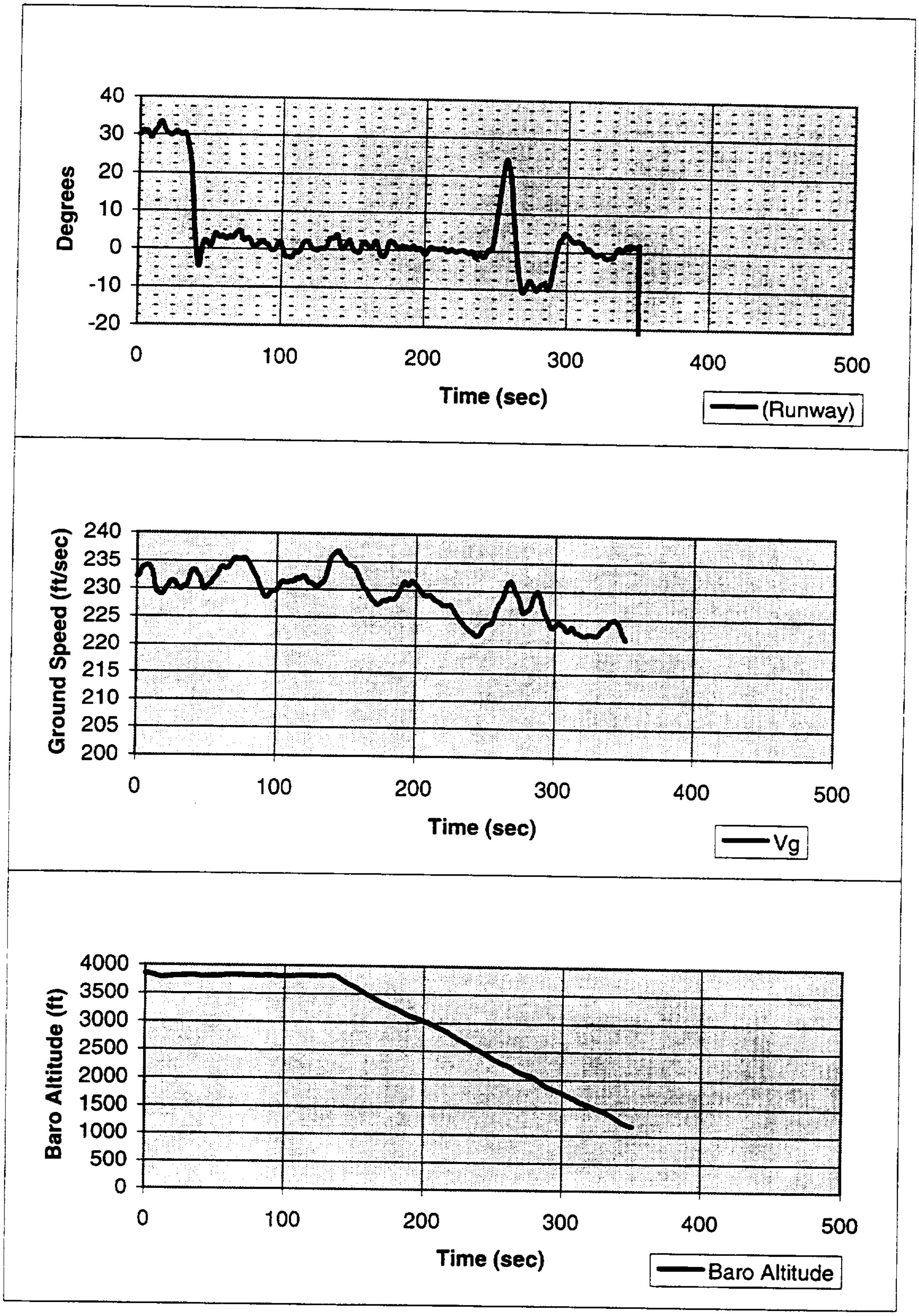

Figure C-19B Fake Blunder Toward Evader Runway "FFAK"
(130 knot Ground Speed, 12.5 knot Wind Gusts, Fog)

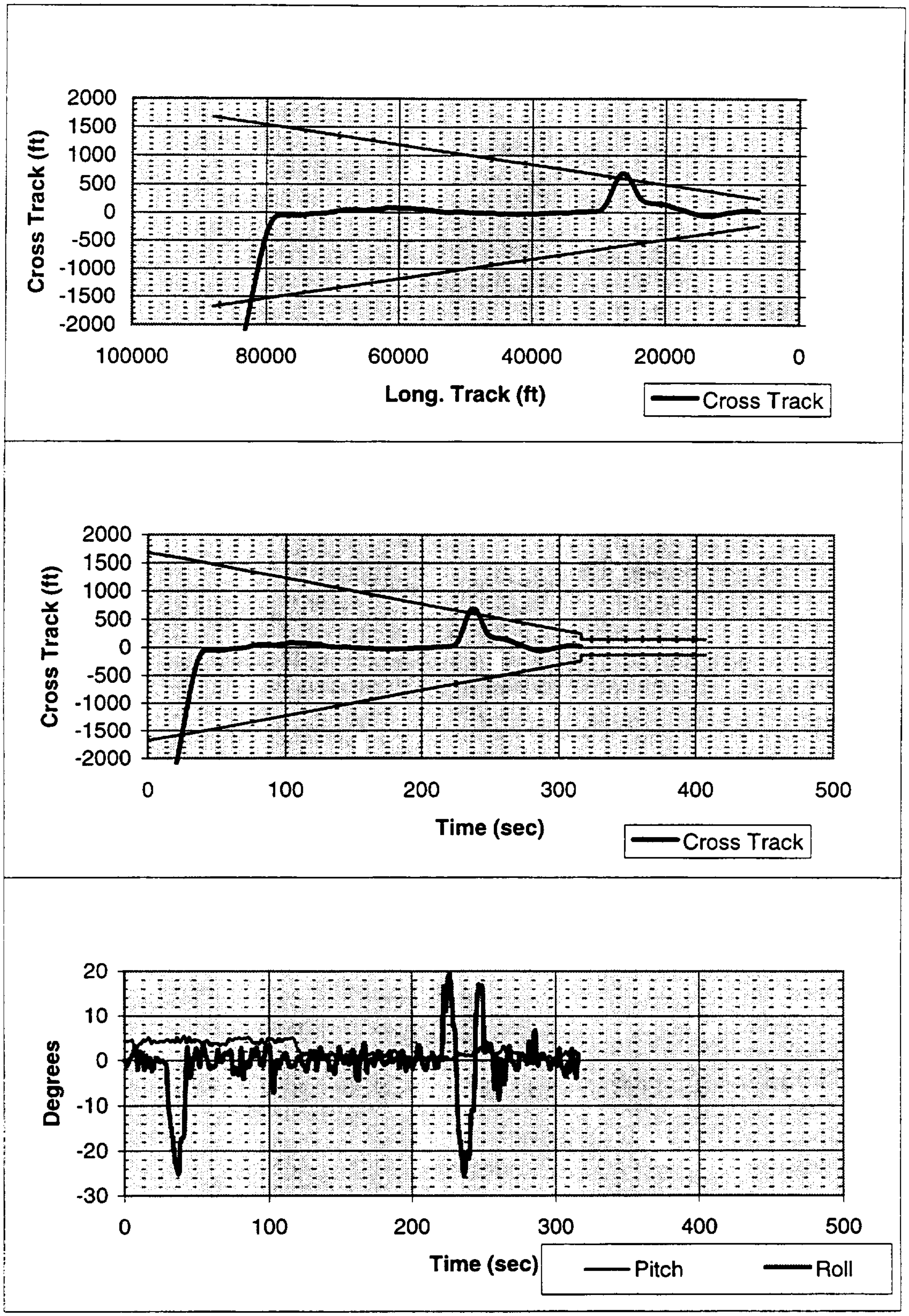

Figure C-20A Fake Blunder Toward Evader Runway "FFAK"
(145 knot Ground Speed, 12.5 knot Wind Gusts, Fog)

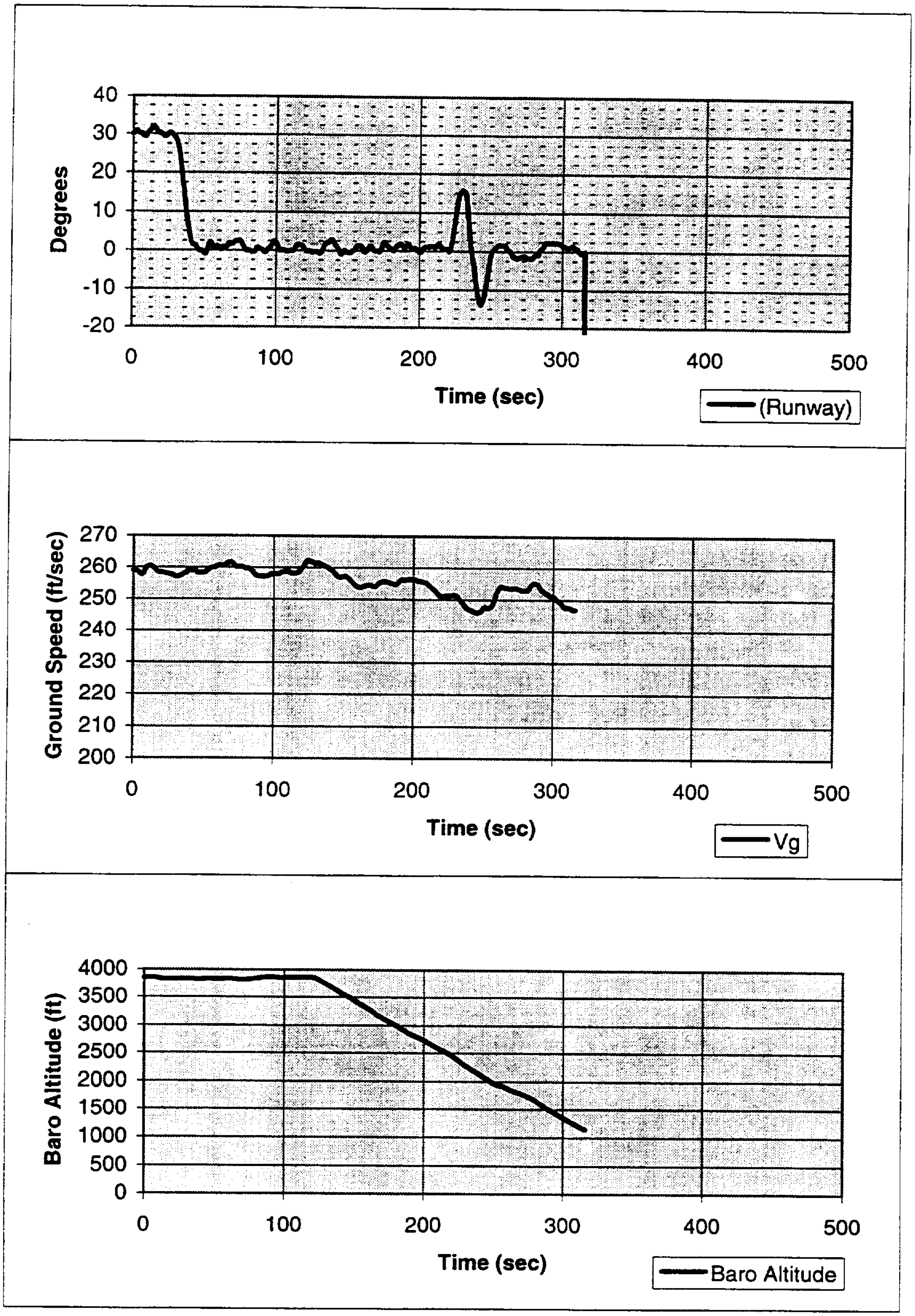

Figure C-20B Fake Blunder Toward Evader Runway "FFAK"
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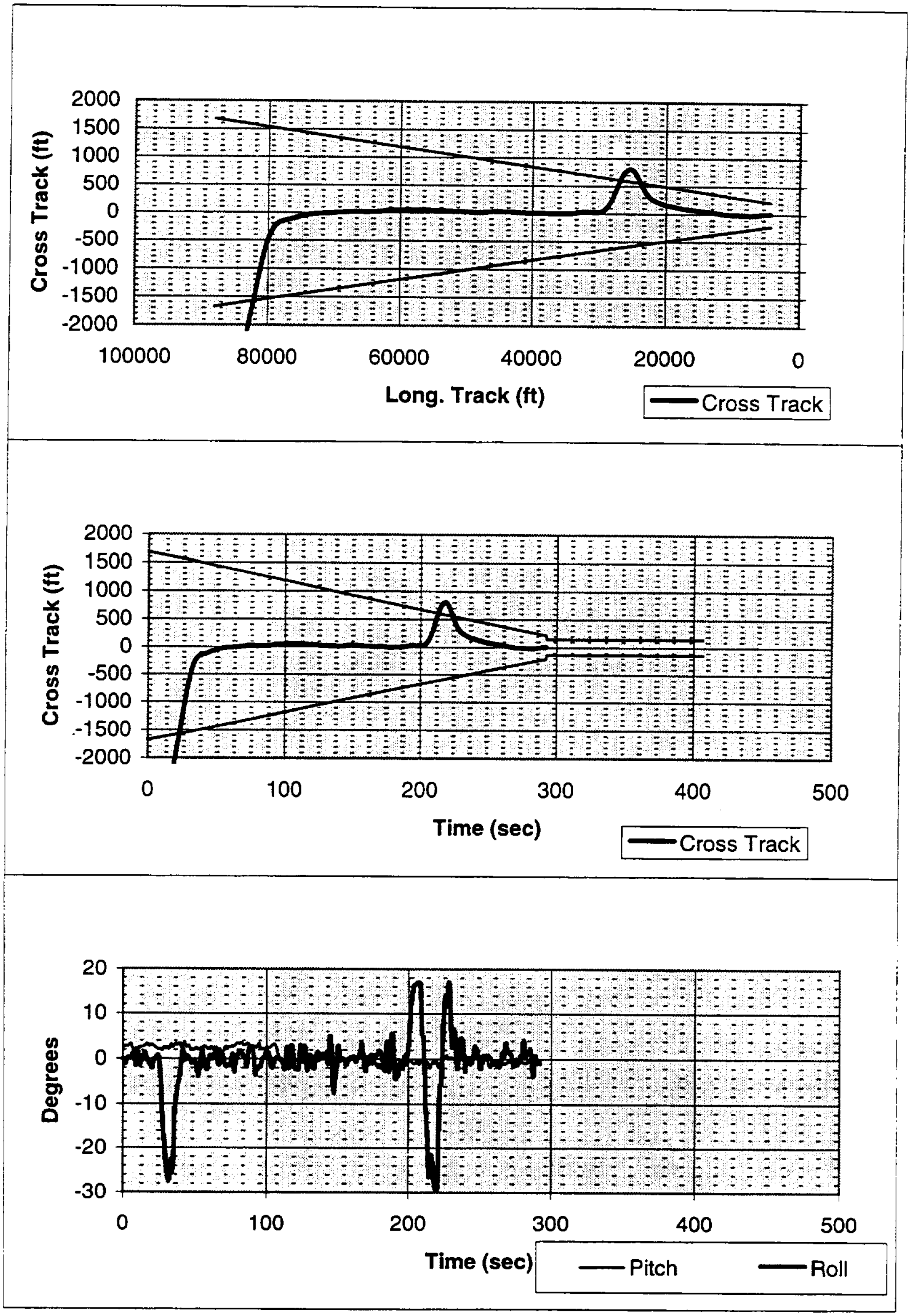

Figure C-21A Fake Blunder Toward Evader Runway "FFAK"
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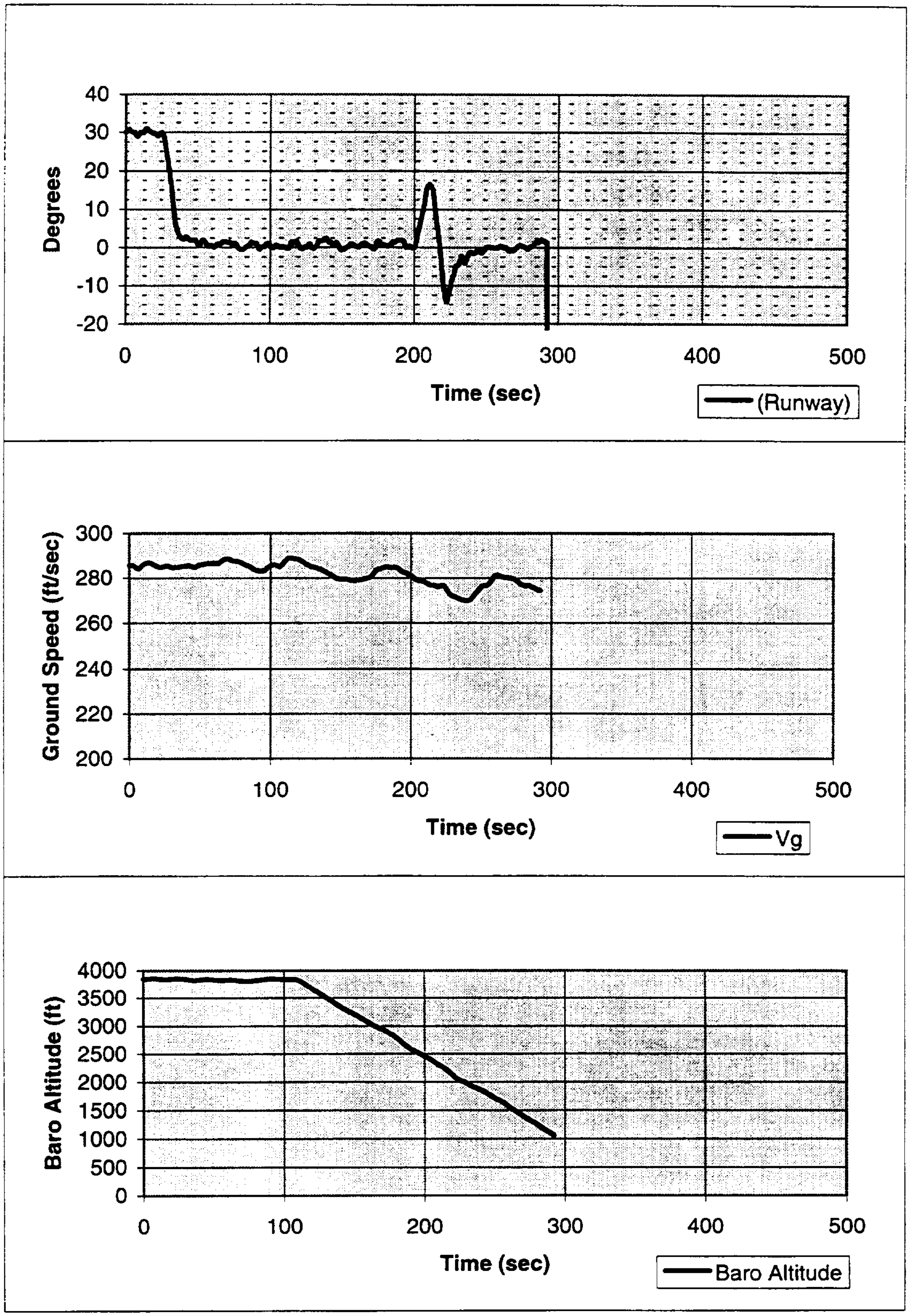

Figure C-21B Fake Blunder Toward Evader Runway "FFAK"
(160 knot Ground Speed, 12.5 knot Wind Gusts, Fog)

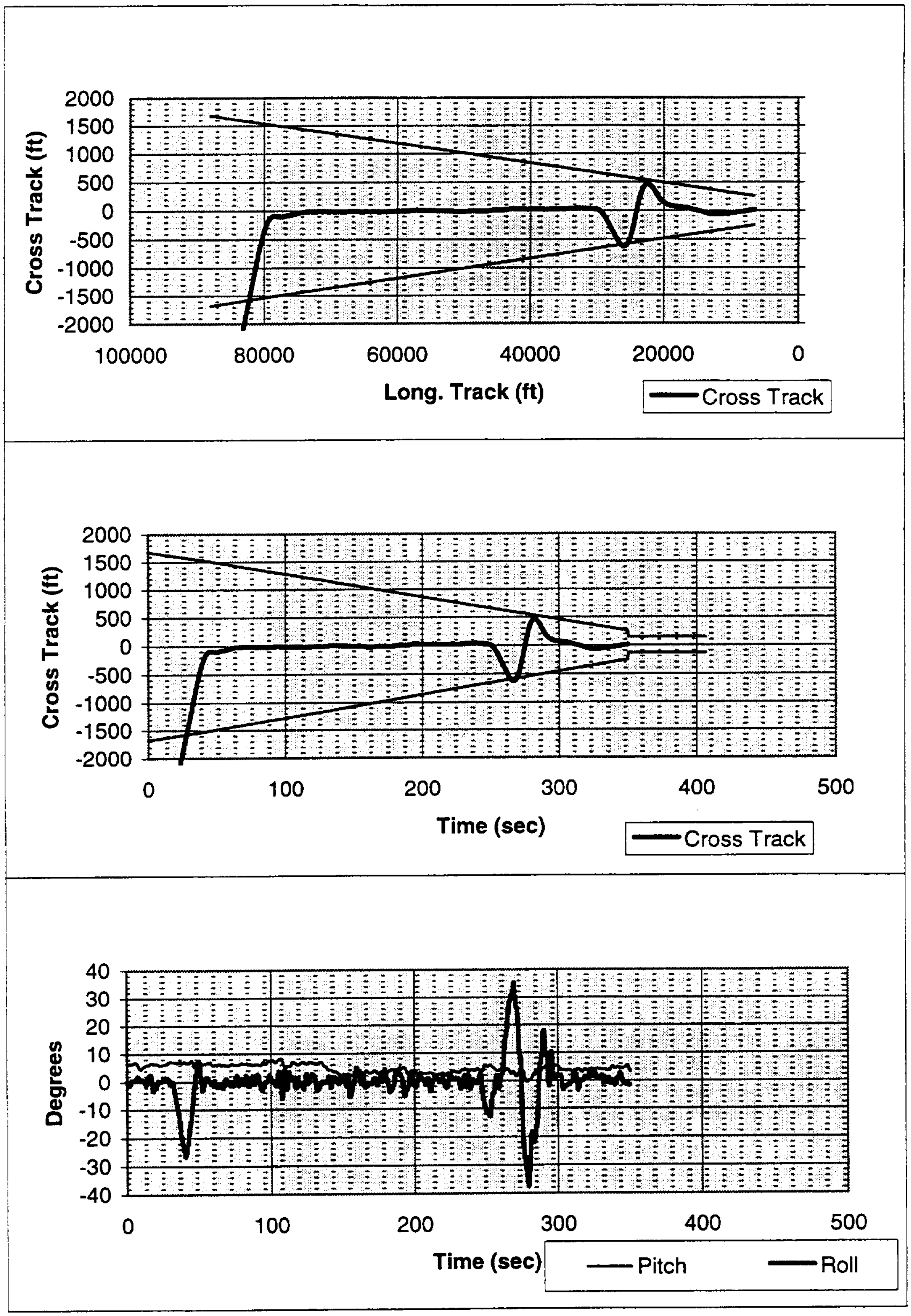

Figure C-22A Drift Away then Overadjust Blunder "FADJ"
(130 knot Ground Speed, 12.5 knot Wind Gusts, Fog)

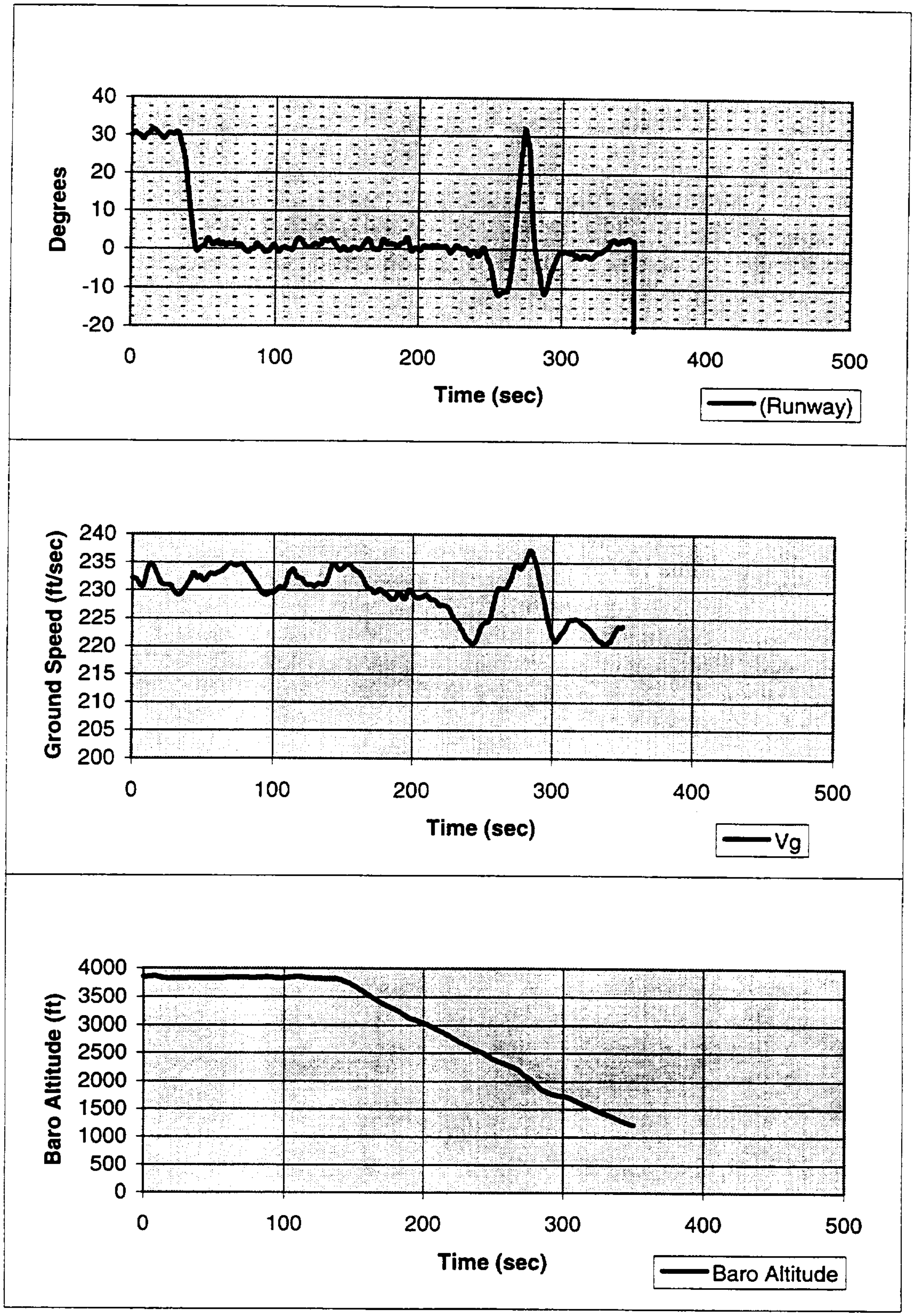

Figure C-22B Drift Away then Overadjust Blunder "FADJ"
(130 knot Ground Speed, 12.5 knot Wind Gusts, Fog)

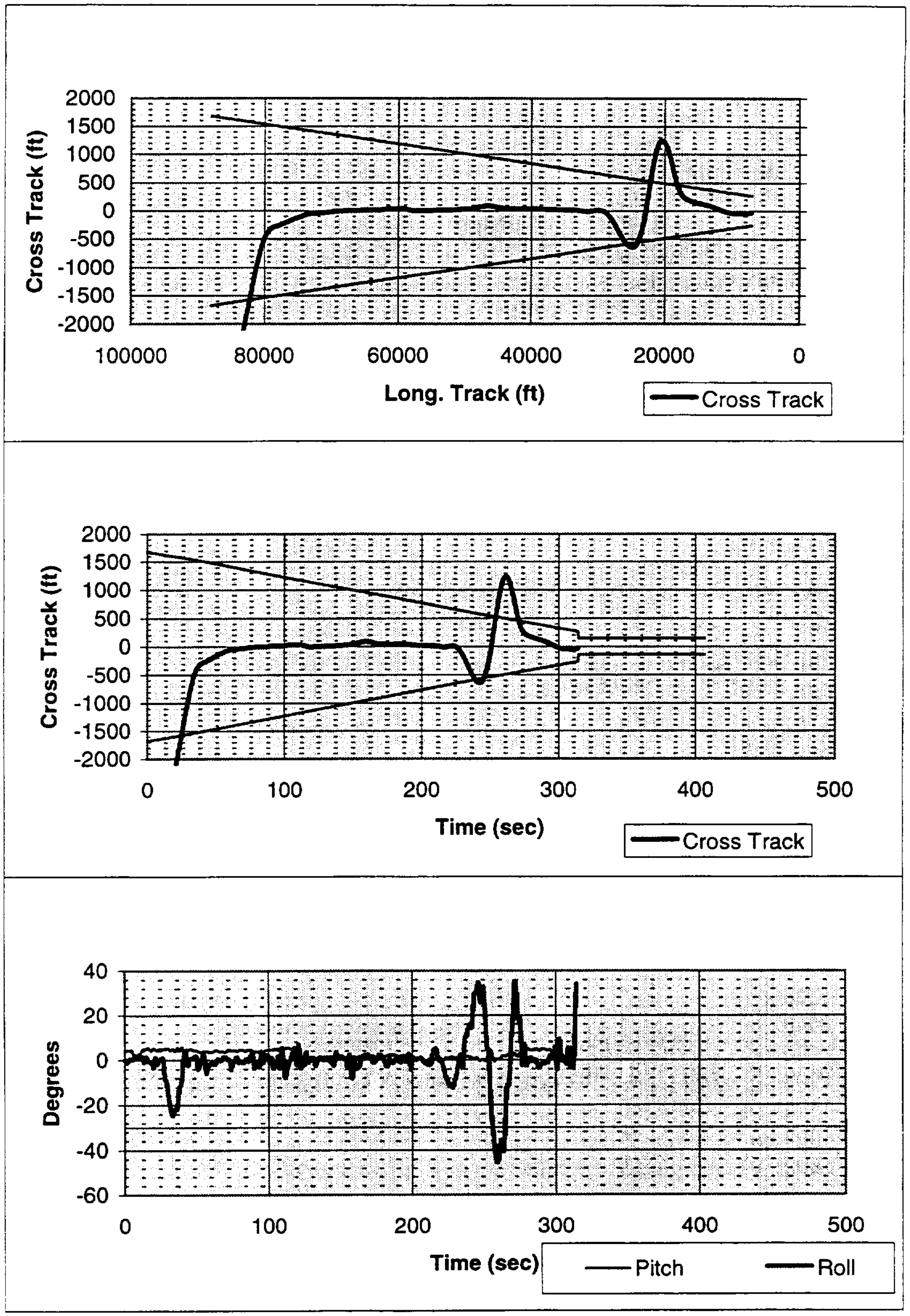

Figure C-23A Drift Away then Overadjust Blunder "FADJ"
(145 knot Ground Speed, 12.5 knot Wind Gusts, Fog)

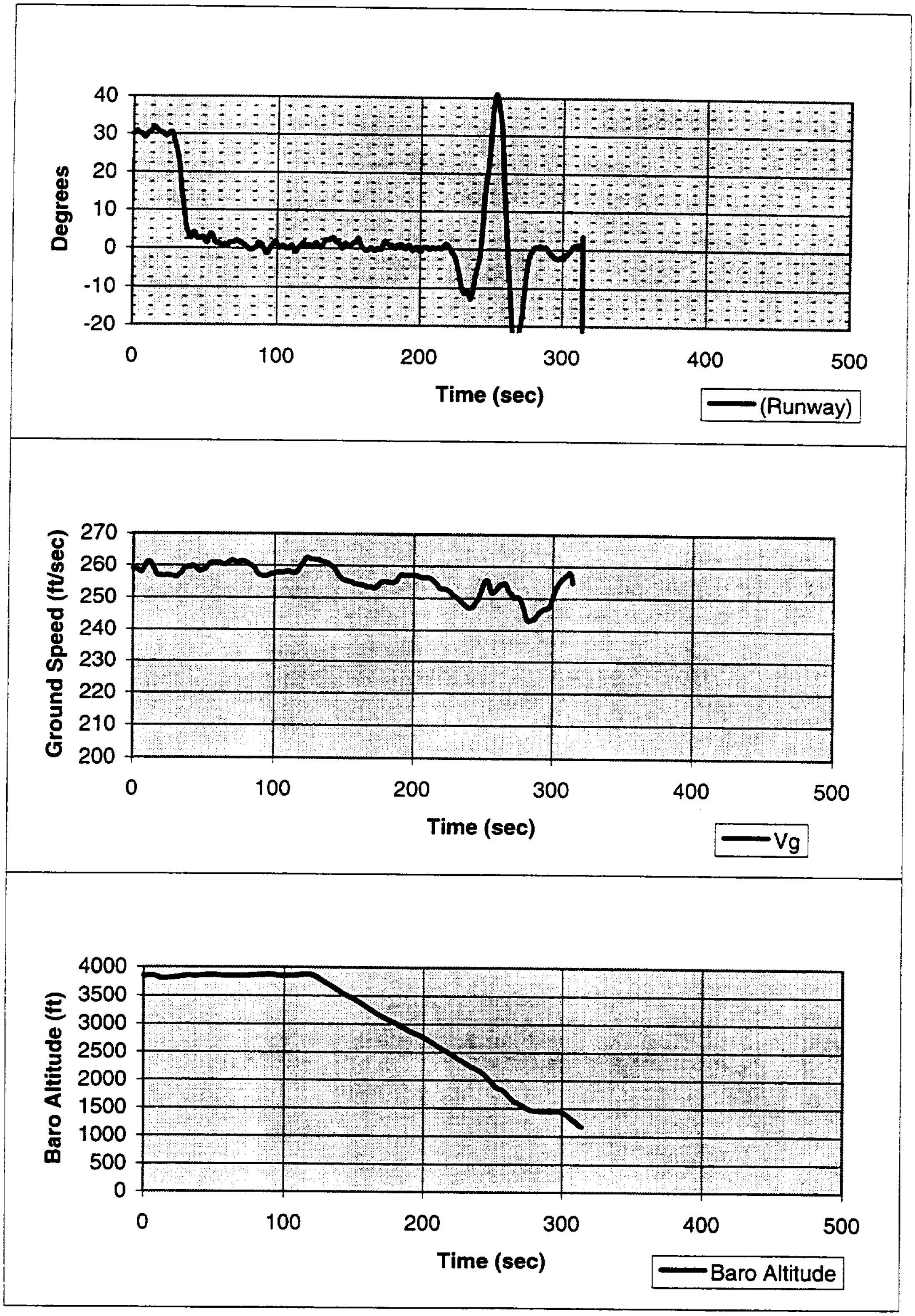

Figure C-23B Drift Away then Overadjust Blunder "FADJ"
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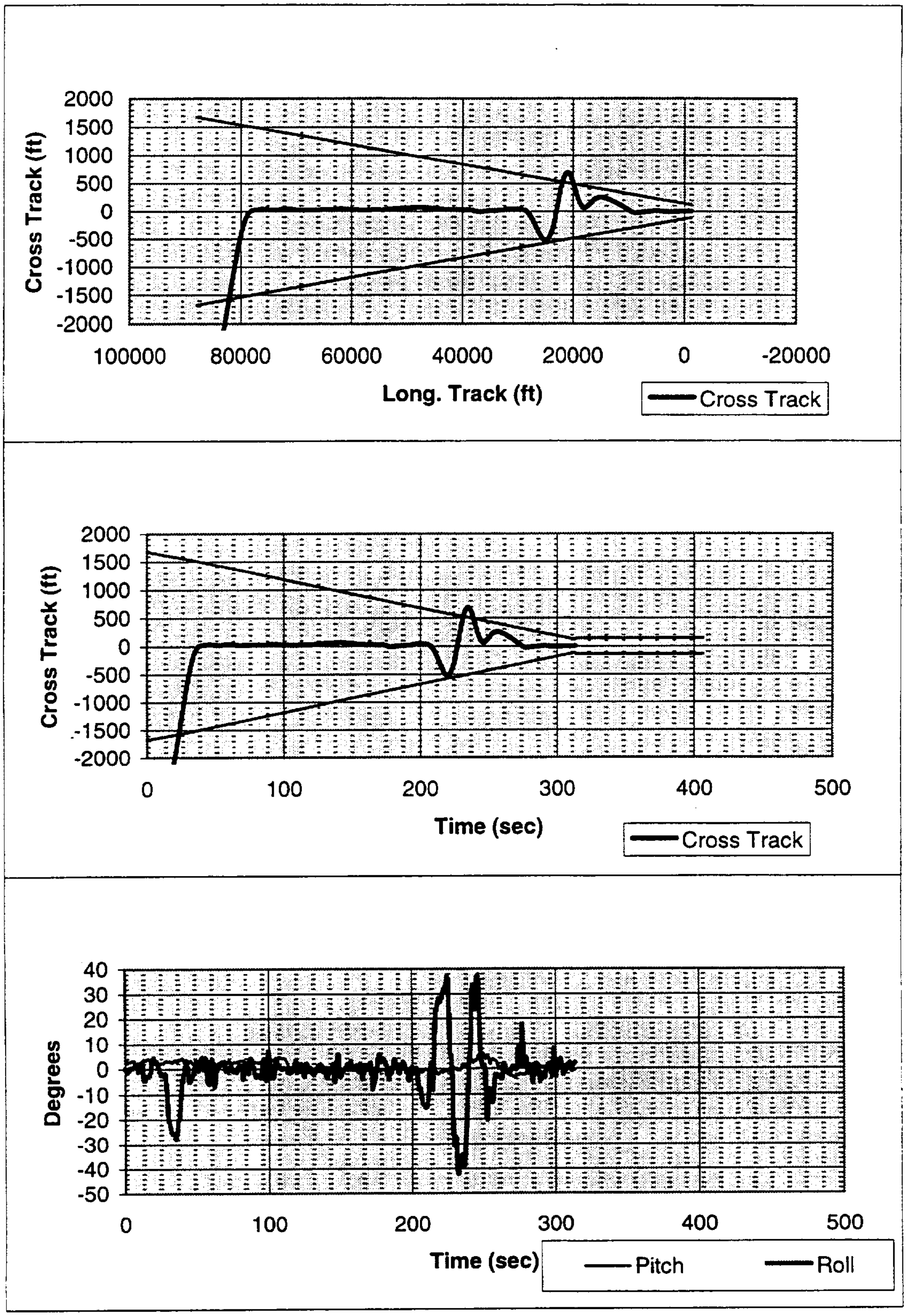

Figure C-24A Drift Away then Overadjust Blunder "FADJ"
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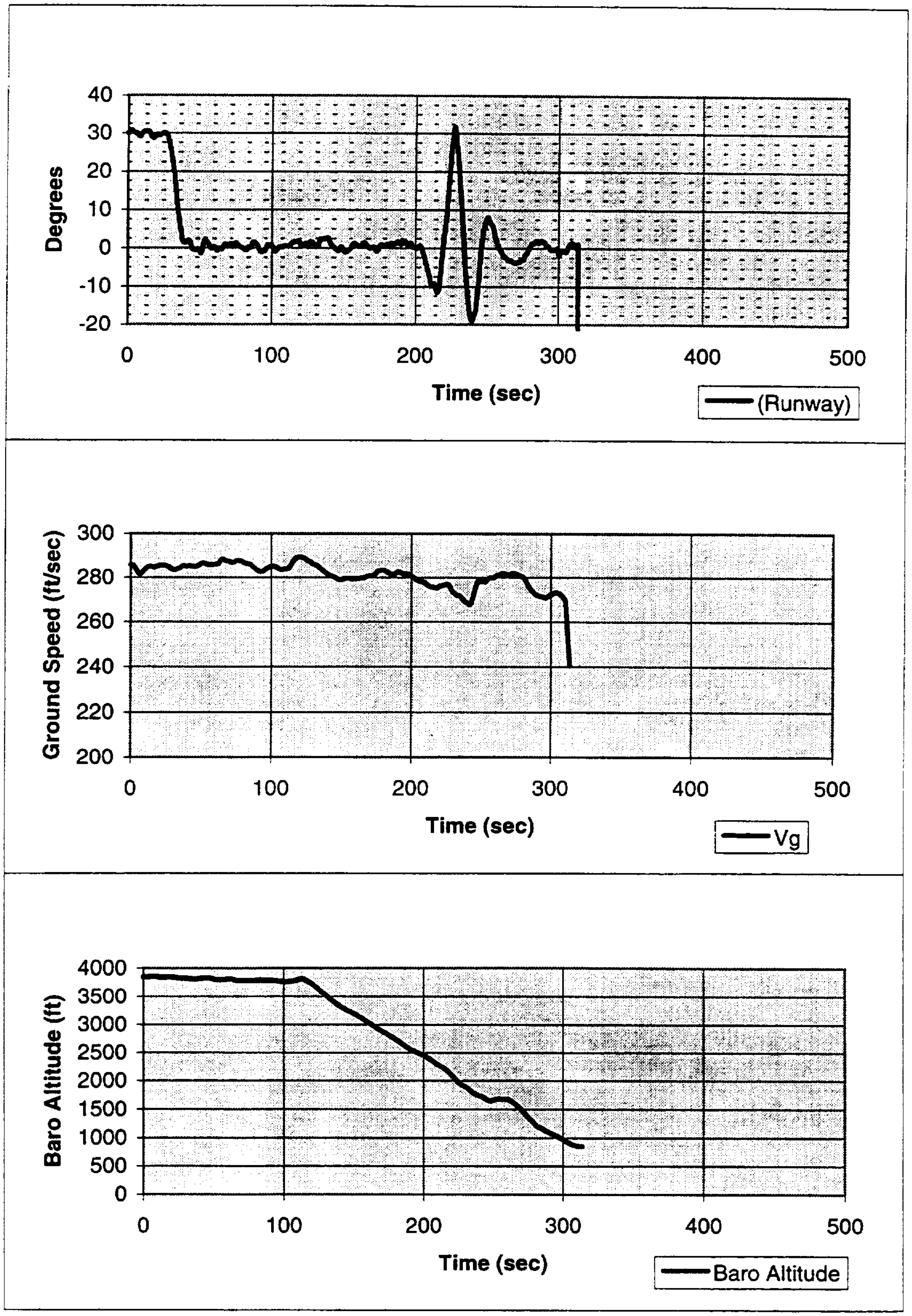

Figure C-24B Drift Away then Overadjust Blunder "FADJ"
(160 knot Ground Speed, 12.5 knot Wind Gusts, Fog)

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13. ABSTRACT ***(Maximum 200 words)***

The current air traffic environment in airport terminal areas experiences substantial delays when weather conditions deteriorate to Instrument Meteorological Conditions (IMC). Expected future increases in air traffic will put additional pressures on the National Airspace System (NAS) and will further compound the high costs associated with airport delays. To address this problem, NASA has embarked on a program to address Terminal Area Productivity. The goals of the TAP program are to provide increased efficiencies in air traffic during the approach, landing, and surface operations in low-visibility conditions. The ultimate goal is to achieve efficiencies of terminal area flight operations commensurate with Visual Meteorological Conditions (VMC) at current or improved levels of safety.

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