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An Investigation of Terrain Avoidance System Flight Test Techniques for High Performance Aircraft

Gregory D. Glen
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To the Graduate Council:

I am submitting herewith a thesis written by Gregory D. Glen entitled "An Investigation of Terrain Avoidance System Flight Test Techniques for High Performance Aircraft." I have examined the final electronic copy of this thesis for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Master of Science, with a major in Aviation Systems.

Dr. Ralph Kimberlin, Major Professor

We have read this thesis and recommend its acceptance:

Dr. Alfonso Pujol, Mr. Richard Ranaudo

Accepted for the Council:
Carolyn R. Hodges

Vice Provost and Dean of the Graduate School

(Original signatures are on file with official student records.)

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An Investigation of Terrain Avoidance System Flight Test Techniques for High Performance Aircraft

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

Gregory David Glen
May 2003

DEDICATION

This thesis is dedicated to LCDR A. Jason Bayer USN, Naval Air Warfare Center, F/A-18 Advanced Weapons Laboratory China Lake TAWS Project Officer. LCDR Bayer died in an unrelated helicopter mishap on March 28, 2002.

DISCLAIMER

The design and technical data contained in this thesis are the result of actual laboratory, flight simulator and flight evaluations of the F/A-18 aircraft. All deficiencies attributed to the aircraft and its systems are the opinion of the author, and may not represent the official position of the United States Navy, Naval Air Systems Command, or the Naval Air Warfare Center. The recommendations made by the author should not be construed as being attributable to any of the aforementioned authorities for any purpose other than the fulfillment of thesis requirements.

ABSTRACT

Controlled-flight-into-terrain incidents have been a leading cause of aircraft related fatalities for a number of years. The development of warning systems to prevent this type of mishap has been constant since the early 1970's. A family Ground Proximity Warning Systems and, recently, Terrain Awareness and Warning Systems have been mandated for use in commercial aircraft in the United States.

Such systems have also been adapted for use in high performance military aircraft, although they tend to be very different from the commercially required variants due to their unique operating environment and aircraft performance requirements.

In this paper, one such system is described in detail, and a set of unique test techniques required to test systems for high performance aircraft is explored. A number of recommendations for testing terrain warning systems intended for use in high performance aircraft are also developed.

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LIST OF ABBREVIATIONS

ACI	Amplifier, Control Intercommunication
ADC	Air Data Computer
AGL	Above Ground Level
AOB	Angle of Bank
ARDS	Advanced Range Data System
ATAMS	Aircraft Target Area Maneuvering Simulation
CFIT	Controlled Flight Into Terrain
DTED	Digital Terrain Elevation Database
DMC	Digital Map Computer
FAA	Federal Aviation Administration (United States)
FLTA	Forward Looking Terrain Avoidance
FMS	Flight Management System
GPS	Global Positioning System
GPWS	Ground Proximity Warning System
HAT	Height Above Terrain
HERR	GPS Reported Horizontal Position Error
HUD	Head Up Display
IFR	Instrument Flight Rules
IMN	Indicated Mach Number
INS	Inertial Navigation System
KCAS	Knots Calibrated Airspeed
LAT	Low-Altitude Tactics
LSO	Landing Signal Officer
MSL	Mean Sea Level

NTSB	National Transportation Safety Board (United States)
ORD	Operational Requirements Document
ORT	Oblique Recovery Trajectory
PDA	Premature Descent Alert
P_{nw}	Percentage of Nuisance Warnings
RADALT	Radar Altimeter
RCC	Range Control Center (Naval Air Warfare Center, China Lake)
RDTED	Re-arced Digital Terrain Elevation Data
RNAV	Area Navigation
ROJ	Reverse Oblique Jink
SOJ	Straight-ahead Oblique Jink
TAMMAC	Tactical Aircraft Moving Map Computer
TAWS	Terrain Awareness and Warning System
TCT	Test Coordination Team
TERPS	Terminal Procedures
TM	Telemetry
VERR	GPS Reported Vertical Position Error
VFR	Visual Flight Rules
VMC	Visual Meteorological Conditions
VRT	Vertical Recovery Trajectory
WonW	Weight on Wheels

1. BACKGROUND

COMMERCIAL AIRCRAFT GPWS SYSTEMS

In the 1970's a number of studies were conducted to examine what could be done about one of the leading causes of fatal aircraft accidents – the so-called Controlled Flight Into Terrain (CFIT). A CFIT event is defined as an instance where an airplane, under the flight crew's control, is inadvertently flown into terrain, obstructions or water without either sufficient or timely flightcrew awareness to have prevented the event [1]. As a result of these studies, the Federal Aviation Administration (FAA) mandated in 1974 that large commercial aircraft be equipped with a Ground Proximity Warning System (GPWS) compliant with Technical Standard Order TSO-C92c. In 1978 the FAA extended the GPWS requirement to Part 135 certificate holders operating turbojet powered airplanes with 10 or more passenger seats [2]. This ruling did not affect turbo-propeller powered (turboprop) aircraft because it was believed that the performance characteristics of turboprop airplanes made them less susceptible to CFIT accidents.

However, later studies, including accident investigations by the National Transportation Safety Board (NTSB), analyzed CFIT accidents involving turboprop airplanes and concluded that some mishaps could have been avoided if GPWS equipment had been used. As a result, the FAA amended the ruling in 1992 to require that all turbine powered aircraft with greater than 10 passenger seats be equipped with GPWS systems [2].

Since the original GPWS requirements were mandated, advances in terrain mapping capability permitted the development of a new family of GPWS system that provides greater situational awareness for flight crews. These systems, known as Enhanced GPWS (EGPWS), have evolved into a type of system more broadly known as Terrain Awareness and Warning System (TAWS). After the crash of an American Airlines 757 equipped with GPWS near Cali, Columbia, the NTSB recommended that the FAA study EGPWS systems and require their installation if they

were found to be effective. Subsequent studies by the Department of Transportation into CFIT accidents between 1985 and 1995 concluded that EGPWS or TAWS systems could have prevented 95-100 percent of them [3]. As a result, in 1998 the FAA mandated that TAWS systems be installed in all commercial aircraft (with some limited exceptions) configured with more than six passenger seats [2].

MILITARY GPWS SYSTEMS

Both tactical and transport class military aircraft have suffered high rates of CFIT accidents as well. The 1996 death of commerce Secretary Ron Brown and 34 others in Croatia in an Air Force C-9 highlighted the need for such systems in military transport aircraft. These aircraft, while not covered under the FAA GPWS or TAWS mandates, can clearly benefit from the same types of systems in use on commercial aircraft. Indeed, most types of large military transport aircraft could use the same systems installed in commercial aircraft, without requiring extensive modifications to either hardware or the protection algorithms due to their similar maneuvering limitations.

As an example applying to tactical military aircraft, CFIT was the probable cause of over 30% of all F/A-18 losses during the first ten years of the aircraft's existence, [4] and is to date the leading single cause of the loss of aircraft in that community. The single-seat layout, frequent task saturation experienced by aircrew, and dynamic flight profiles combine to make an extremely strong case for inclusion of terrain avoidance systems in such aircraft. The frequent nap-of-the-Earth profiles flown by many rotary wing platforms make them prime candidates for such systems as well.

However, the operating environment and mission of high-performance tactical aircraft provide unique challenges for designers of GPWS systems. Many tactical aircraft use computer systems and displays that are integrated in such a manner as to make it difficult to add external functions

to the overall avionics systems without extensive integration efforts. In addition, the flight envelopes of tactical aircraft are sufficiently different from transport class aircraft as to make the warning algorithms substantially different.

2. GPWS/TAWS SYSTEM FUNCTIONALITY

GROUND PROXIMITY WARNING SYSTEM

Federally mandated GPWS systems for commercial aircraft initially were required to alert the aircrew to potential CFIT situations according to the modes [5] shown in Table 2-1. This type of system uses inputs from aircraft sensors for determining altitude, altitude rate of change and other aircraft conditions such as gear or flaps positions, and provides a warning of potential contact with the ground, taking into account crew recognition and reaction time. Aircraft sensor inputs to the system can include a radio altimeter, air data computer or barometric altimeter, and deviation from ILS glideslope and localizer. The system outputs include visual and aural alerts and warnings when it detects by calculated position rate-of-change that the aircraft is closing with terrain. This type of system, though very useful, provides limited CFIT protection because it is unable to account for rapidly changing terrain under the aircraft or obstructions in the flight path. In addition, when in landing configuration, (gear and flaps deployed) warnings are inhibited for all but excessive rates of descent, limiting protection during approaches.

Table 2-1
GPWS Protection Modes

	Protection
1	Excessive Rates of Descent
2	Excessive Closure Rate to Terrain
3	Negative Climb Rate or Altitude Loss After Takeoff
4	Flight Into Terrain When Not in Landing Configuration
5	Excessive Downward Deviation From an ILS Glidescope
6	500 ft Callout on Non-Precision Approach

TAWS

Current regulations require systems compliant with TSO-C151a be installed in most commercial aircraft [2]. These systems offer greater protection from CFIT than GPWS because of their Forward Looking Terrain Avoidance (FLTA) capability and Premature Descent Alert (PDA) functionality. TAWS systems also incorporate improved situational awareness displays and provide the basic GPWS functionality contained in earlier systems. These systems are broken into two types, Class A and Class B systems, mandated depending on aircraft operating criteria as shown in Table 2-2 [6].

TAWS systems utilize terrain, airport and obstacle databases, employing the global standard WGS-84 spheroid for latitude/longitude reference to provide flight crews with an improved predictive terrain hazard warning function. The predictive function is achieved by feeding the aircraft's known position (as determined by a flight management system or by GPS) to a terrain database, enabling the computer to predict terrain ahead and to the side of the aircraft's flight path. By referencing terrain and airport databases, TAWS can warn of descent below safe vertical profiles when the aircraft is in a landing configuration and there is no instrument landing system glidescope signal present.

Class A systems also incorporate a color display allowing rapid identification of terrain hazards together with a graphical display of the surrounding terrain. The aircraft position is shown on the display either by GPS alone or through the flight management system. Specific TAWS functionality is described in the following sections.

Table 2-2
TAWS Class A and B Summary of Requirements

TAWS Class	Operating Rule	PAX Seats	FLTA	PDA	GPWS Modes (DO-161A)	FMS/RNAV or GPS	Mandatory Terrain Display	Terrain/ Field Database
A	121	All	YES	YES	1-6	Either	YES	YES
A	135	>9	YES	YES	1-6	GPS	YES	YES
B	135	6-9	YES	YES	1,3,6	GPS	NO	YES
B	91	6+	YES	YES	1,3,6	GPS	NO	YES

TAWS Minimum Requirements

Forward Looking Terrain Avoidance

The TAWS Forward Looking Terrain Avoidance (FLTA) warning capability "looks" ahead of and to the side of the aircraft's predicted flight path and issues a warning if terrain or obstacles penetrate the search volume, where the defined search volume varies as a function of flight phase and aircraft maneuvers. The flight phase must be determined by the TAWS computer using available inputs in order to ensure the proper mode is enabled where required. The following definitions are generally recognized, though differences are allowed as long as they are compatible with terminal procedures (TERPS) and standard instrument approach procedures [6]:

a) Enroute Phase: The aircraft is more than 15 nmi from the nearest airport or the conditions for Terminal, Approach, and Departure Phases are not met.

b) Terminal Phase: The aircraft is 15 nmi or less from the nearest airport, the range to the nearest runway threshold is decreasing and the airplane is at or below a straight line drawn between the two points specified in Table 2-3 relative to the nearest runway.

c) Approach Phase: Distance to nearest runway threshold is less than 5 nmi, height above the runway threshold is less than 1,900 ft, and distance to threshold is decreasing.

Table 2-3
Height Above Versus Distance To Runway

Distance to Runway	Height Above Runway
15 nmi	3,500 ft
5 nmi	1,900 ft

d) Departure Phase: The aircraft is defined to be in the departure phase from the point when it transitions to flight after leaving the runway, until it achieves an altitude of 1,500 ft AGL. The system must use some combination of sensor parameters to determine when the aircraft is on the ground, and when it has transitioned to flight. Commonly used sensor inputs include weight-on-wheels indications measured at the landing gear and airspeed thresholds.

TAWS System Basic GPWS Functionality

In addition to the TAWS specific functionality listed above, the required TSO-C92 GPWS functionality must be included as well. These basic GPWS protection modes, shown in Table 2-1, are required to function even if the TAWS warning functionality fails due to a sensor, processor, or loss of the TAWS terrain database.

3. TESTING GPWS/TAWS SYSTEMS INSTALLED ON COMMERCIAL AIRCRAFT

CERTIFICATION REQUIREMENTS

Terrain warning systems, like all equipment installed on U.S. registered aircraft, must obtain airworthiness approval from the FAA through the Type Certification or Supplemental Type Certification process. This involves documenting the design, performance, and all details of the system installation and integration with each type of aircraft [7]. In addition, a System Safety Assessment must be conducted to establish all hazards associated with the installation, and to define the failure modes and probability of failure, as well as impacts to aircraft operations, and required mitigations to defined hazards.

FLIGHT TEST CONSIDERATIONS

The level of flight test required to validate a particular TAWS system installation depends on the type of aircraft, avionics structure, and whether or not that particular system has been certified in another application [7]. First time installations for a particular system or type of aircraft almost always require flight test demonstration of required functionality. The addition of new sensors to previously certified systems usually requires a limited flight test program to demonstrate system operation in the modes affected by the sensor inputs. In the case where upgraded TAWS systems are installed in a particular model aircraft that was previously equipped with some measure of GPWS equipment from the same manufacturer, flight testing of the previous functionality may not be required.

FLIGHT TEST TECHNIQUES

In general, flight testing is as simple as demonstrating that each mode shows proper activation, deactivation after the cause of the warning is removed, and freedom from nuisance warnings.

GPWS Testing

The methods required for demonstrating GPWS are described in the following sections [8].

Mode 1

Establish several descent rates below 3,000 ft AGL, continuing until the warning is activated, then pull-up until the warning is cleared. Minimum altitudes to safely recover the aircraft at each descent rate are used as a safety back-up should the system fail to issue a warning.

Mode 2

Flight across smoothly rising terrain in level flight at 500 ft above the highest terrain feature at different flap and gear settings.

Mode 3

After a normal takeoff, climb to 300 ft AGL and slow climb rate until a slight descent is initiated to trigger a warning.

Mode 4

Fly an approach with the appropriate approach flaps setting while leaving the gear up until the warning threshold is reached. A go-around is initiated at a safe altitude.

Mode 5

Conduct ILS approaches (During VMC) at varying deviations from the glide slope to trigger warnings.

TAWS Functionality

TAWS functionality can be tested in a similar manner with relatively low risk [7] because of the benign nature of the maneuvers required to initiate and clear warnings.

FLTA Mode

Flight test can be conducted in any area where the terrain or obstacle elevation is known. The terrain or feature can be overflown while straight and level at no lower than 300 ft above the known elevation to verify warning functionality.

PDA Mode

The premature descent mode can be tested in any area within 10 nmi of an airport that is included in the terrain database. The threshold limits for the warnings can be easily and safely explored to demonstrate proper system operation.

4. APPLYING GPWS/TAWS SYSTEMS TO HIGH PERFORMANCE AIRCRAFT

APPLICABILITY OF GPWS/TAWS SYSTEMS

Ground Proximity Warning and TAWS systems can be implemented in high performance military aircraft, though both the integration and operation of the systems is usually quite different from systems intended for use in commercial aircraft. The operating environment and integration challenges combine to make these systems considerably different from their commercial counterparts.

Integration

Most high performance aircraft have unique avionics systems structured for their particular mission. These are usually based on state-of-the-art technology and are focused on providing the high performance required, as well as being able to fit in a physically confined location. In addition, the system architecture many times is distributed throughout the airframe with considerable redundancy to increase survivability, but at a cost of increased complexity. This requires that other systems to be integrated must conform to unique interface requirements, which in turn drives a requirement for dedicated system development.

Operation

In addition to integration challenges, the operating envelope of high performance aircraft drives system requirements to much greater complexity. The fact that the aircraft routinely operate at high speed near terrain requires that the protection algorithms be based on completely different assumptions than those in use in commercial systems. For instance, the altitude clearance allowed by such systems prior to issuing warnings must by virtue of the aircraft operating envelope be much smaller than commercial systems. In addition, the variety of external

stores configurations, and their effects on aircraft performance and the available recovery margin adds to the problem. The effects of nuisance cues on the aircrew also drive elements of the system design as well. Repeated nuisance cues can drastically alter the assumptions of aircrew response, which must be assumed and modeled into the algorithms.

Flight Testing

The following sections describe one system designed for use in a tactical military high performance aircraft, and the unique challenges presented by the environment in which it was designed to operate, as well as the challenges in testing its proper operation safely.

5. TAWS ON THE F/A-18

OVERVIEW

The Enhanced Terrain Awareness and Warning System (TAWS) is the second generation of the embedded Ground Proximity Warning System (GPWS), which was originally implemented on F/A-18C/D model aircraft [11]. Both GPWS and TAWS are safety back-up systems designed to reduce the probability of a Controlled-Flight-Into-Terrain (CFIT) type mishap in Navy tactical aircraft by alerting the aircrew when ground impact is imminent.

The original versions of GPWS were designed by the Naval Air Systems Command Embedded GPWS Integrated Product Team (IPT) and documented in the form of an "Algorithm Design Report". This report was provided to the F/A-18 prime contractor (McDonell Douglas) who implemented the design in assembly language on the aircraft's mission computers. After implementation, the algorithm was laboratory tested in the Manned Flight Simulator prior to flight testing on a test aircraft. When the TAWS program was initiated, the decision was made to have the Embedded GPWS IPT not only design the algorithm, but also implement it in the Ada high level programming language. This software was then hosted on the aircraft's digital map computer to take advantage of the stored digital terrain data without facing the difficulty of transferring that information to the aircraft mission computers. The algorithm is run on the Tactical Aircraft Moving Map Computer (TAMMAC) using inputs from aircraft sensors and the mission computers.

OPERATIONAL CONCEPT

The original GPWS system is limited by its primary altitude sensor, the radar altimeter (RADALT). Because the RADALT is a look-down sensor, it cannot be used to determine the terrain characteristics ahead of the aircraft. A history of the terrain behind the aircraft is available

and could be used in some instances, but is not indicative of the approaching terrain. This leaves effectively no protection against flight into rising terrain or during flight over mountains. The TAWS system overcomes this limitation with the introduction of accurate aircraft positioning and a digital terrain database. The TAWS computes the expected recovery trajectory, in three dimensions, and compares it with Digital Terrain Elevation Data (DTED). One critical requirement is having accurate aircraft positioning relative to both the DTED database and the world. The TAWS system combines data from many sensors to determine a position in three-dimensional space that is used as the starting point for the recovery trajectory. When the recovery trajectory intersects the DTED database, a warning is issued to the aircrew. The warning is presented as an arrow on the Head-Up Display (HUD) that indicates the direction for recovery, and a directive voice warning that indicates the proper response based on the flight condition. The arrow and the voice warning continue until the warning condition no longer exists. The voice warnings available are: "Pull-Up…Pull-Up", "Roll-Left…Roll-Left", "Roll-Right…Roll-Right", "Power…Power", and "Check Gear".

In the event that accurate positioning data or the DTED database is unavailable, the TAWS enters a mode that bases warnings solely on the altitude required to recover. This "flat Earth" mode is very effective over water, as was proven during the earlier GPWS development.

SYSTEM TRADEOFFS

The TAWS system was designed to minimize nuisance warnings. Nuisance warnings are defined as warnings that the aircrew deems unnecessary based upon their intentions and view of the terrain. If nuisance warnings are accepted as a "necessary cost" of protecting the aircraft and aircrew, TAWS becomes significantly less effective. This negative training causes the aircrew to question each warning, thus delaying the start of the recovery if the aircrew deems the warning

valid. Any delay in responding to the warning will have catastrophic consequences as the aircraft will no longer have sufficient altitude to successfully recover since TAWS warnings are issued at the last instant that recovery is possible given the aircraft's calculated performance. This design bias towards a minimization of nuisance warnings is required for this system because of the low-altitude and dynamic maneuvering mission requirements of the F/A-18. TAWS Warnings normally occur three to seven seconds prior to terrain impact. The system requirements are for a nuisance warning percentage of less than 8% (threshold) with an objective of less than 3%.

DESIGN DECISIONS

Configurable Parameters

The TAWS was intended to provide support for multiple platforms without software modifications. (e.g., F/A-18C/D and F/A-18E/F). Therefore platform-specific characteristics were identified and encapsulated as "configurable parameters" whose values may differ for each installation. These parameters are loaded into predefined locations in the Digital Mapping Computer (DMC) so that TAWS can effectively be customized for the desired platform, and changes to the algorithm can be made without software modifications. The configurable parameters are presented in appendix A, Table A-1. These parameters are loaded into the aircraft on the mission data card inserted from the cockpit.

I/O Approach

The TAWS system is hosted on the Tactical Aircraft Moving Map Computer (TAMMAC) and accepts its inputs from the aircraft mission computers in the form of three MIL-STD-1553 messages. Each message includes a counter, which allows the system to ensure that the messages

come from the same MC frame, and are from a later frame than the last data received and processed.

TAWS OPERATIONAL MODES

The TAWS uses three primary modes to define the level of operation, terrain database availability, and warning condition. These three primary modes are BYPASS, COAST and OPERATE.

BYPASS Mode

When System Mode is set to BYPASS, the TAWS processes all required inputs, but does not execute warnings. The system mode is set to BYPASS when the sensor hierarchy determines that the system does not have enough sensor information to provide protection, or the aircraft is in the Weight-on-Wheels (WonW) condition.

COAST Mode

When System Mode is set to COAST, the TAWS processes all components and issues warning cues based on an extrapolated height above terrain. The System Mode is set to COAST when the System Mode is not in BYPASS, and DTED or accurate positioning is unavailable and RADALT data is unavailable. Over relatively flat terrain, the extrapolated height above terrain is based upon the last known terrain elevation. In the case where the last known height above terrain was varying (ie above mountainous terrain), the COAST mode is not used.

OPERATE Mode

When the System Mode is set to OPERATE, the TAWS processes all components and issues warning cues based upon measured height above terrain. The System Mode is set to OPERATE when the conditions for BYPASS and COAST are not met.

Terrain Definition Mode

In addition to the primary operating mode, the system defines a Terrain Definition Mode which is determined based on whether or not the TAWS is using the Re-arced Digital Terrain Elevation Data (RDTED) database for protection. The Terrain Definition Mode can either be DTED or FLAT EARTH.

DTED

When the Terrain Definition Mode is set to DTED (DTED mode), the TAWS provides protection against flight into all types of terrain (rising, level, and descending). The Terrain Definition Mode is set to DTED when RDTED is available for the current location, the TAWS has accurately determined its position, and the system is not in the landing phase.

FLAT EARTH

When the Terrain Definition Mode is set to FLAT EARTH, the system provides warnings only against descending flight into level or descending terrain. The Terrain Definition Mode is set to FLAT EARTH when RDTED is unavailable (including over the ocean), or when the system cannot accurately determine its position, or is in the landing phase.

SYSTEM WARNINGS

The system provides several different types of warnings loosely grouped into either GEAR or TRAJECTORY warnings.

GEAR Warning

A GEAR warning is issued when the system determines that a gear-up landing is about to occur while in the landing phase of flight. The criteria for setting the GEAR warning is:

- The Aircraft is below 150 feet AGL, and

- Is below 200 KCAS, and
- The aircraft is descending, and
- More than 60 seconds have elapsed since a waveoff or takeoff, and
- The landing gear is not down and locked.

While in the landing flight phase, the system operates in the FLAT EARTH mode. Protection is still provided by comparing the altitude required to recover the aircraft and the height above terrain, but once a landing attempt is confirmed, the TAWS adds additional protection to ensure that a gear-up landing is not about to happen. The system Landing Phase is defined as:

- Altitude less than 500 feet AGL, and
- Airspeed less than 200 KCAS, and
- More than 60 seconds since a waveoff or takeoff.

The GEAR Warning Mode is cleared when the TAWS receives the down-and-locked indication, the aircraft begins climbing, the height above terrain climbs above 150 feet, or the system leaves the landing phase. In all warning and cancellation conditions, the warning condition (or cancellation criteria) must be met for three frames before the warning mode is actually set (or cleared) in the fourth frame. These persistency timers protect the TAWS from erroneously setting warnings (or clearing warnings) based on bad transient input data.

TRAJECTORY Warning

A TRAJECTORY warning is issued when the system determines that a high probability of a CFIT exists. That is, the current flight path will intercept the ground unless an aggressive

recovery is initiated immediately. This protection is available at all airspeeds and flight conditions. However, TAWS Warnings are inhibited when:

- Within 6 seconds of WonW to weight-off-wheels transition, or
- Within 1.1 seconds of transitioning from the BYPASS mode, or
- The TAWS computed height-above-terrain is less than zero.

SYSTEM SENSOR INPUTS

Signal processing selects data from many sources and produces what is deemed the most accurate Height Above Terrain (HAT), height above Mean Sea Level (MSL), aircraft velocities, position, and accelerations. Two basic sources of height above terrain are used: the RADALT, and the difference between aircraft MSL altitude and the terrain height from the RDTED database. Error estimates are computed for each of these sources so that the proper weighting can be made for each one.

To achieve full performance, data is required from the following aircraft systems: Inertial Navigation System (INS), RADALT, Air Data Computer (ADC), and GPS. RDTED is also required from the Digital Map Computer (DMC). Some failures (or unavailability) of these inputs will invalidate the TAWS, while other failures will only degrade performance to varying degrees.

Table A-2 (Appendix A) shows the hierarchy of sensors used for each input to the TAWS and the effects of sensor failures. As an example, TAWS is in its fully capable mode when the INS reports valid attitude and acceleration, GPS is used for position (either aiding the INS or stand-alone), and DTED is available.

Terrain Height Determination

The TAWS algorithm queries the DMC to acquire DTED information. The DMC returns RDTED, which contains terrain heights (gridposts) spaced roughly 150 meters apart at mid-latitudes. The DMC returns an elevation, which is the weighted average (using bilinear interpolation) of the four closest RDTED gridposts surrounding the input latitude and longitude. The RDTED was derived from the original Level I DTED, which has gridposts spaced at 3 arc seconds, which equates to 100 meters at the equator, and decreases toward the poles. The DTED is re-arced to support the TAMMAC map scale. As more precise DTED becomes available, the TAMMAC will handle the Level-II data and pass it to the TAWS with no loss of functionality, but with greater precision.

The TAWS algorithm requests RDTED from the position on the globe that is one frame ahead of the current aircraft position instead of the "current" position. This allows the system to measure the difference in neighboring gridpost heights, by collecting data one frame in front of the aircraft as well as behind. The TAWS uses differences in neighboring gridpost heights in calculating a nuisance warning buffer. The TAWS converts the DTED into feet and sets up an array of three DTED points: in front of (next), under (current), and behind (last) the aircraft. Three DTED points were chosen to minimize potential map registration errors in terrain data local to the aircraft position. It looks up the next point each frame, passes the value of next to current, and current to last. The "current" values are used for calculations, while the others are kept for determining variation in heights at neighboring locations.

The TAWS calculates the terrain variation by measuring the difference in DTED terrain heights both behind (where the aircraft has been) and ahead (where it is going) of the current point. "Behind" is measured by finding the difference between DTED heights every frame, and exponentially decaying the values over time, so the variation over the last 2 gridposts (approximately 1000 ft) is weighted at 50%. This method measures both jaggedness and rising or

falling terrain. "Ahead" is measured by a "terrain roughness" parameter passed to the algorithm from the DMC, which finds the variation from a smooth slope of the next 15 gridpost heights (approximately 7400 ft). Fifteen was chosen because it represents the length of a typical recovery trajectory. These two measures are then averaged to get the estimate of terrain variation, which determines how large the DTED and RADALT errors might be.

Determining Aircraft Position

The TAWS needs accurate position and altitude information to properly process potential warning conditions. The system then uses the position error as an estimate of what is commonly known as "map registration error". The DTED database is populated with terrain heights for specific latitude / longitude locations, and if the aircraft queries the database with a location that it believes it is at, but in reality the aircraft is somewhere else, a map registration error occurs because the terrain height returned is for a location other than where the aircraft is.

When the GPS errors are acceptable (less than a defined limit of 80 ft), the position error parameter is set to the GPS horizontal position error (HERR) returned by the GPS receiver. If the GPS validity bit is FALSE, the position error parameter grows at the rate of 2 ft/sec. This is the expected INS drift rate, based on historical data for the ASN-139 INS. The value of 80 ft was chosen for two reasons: first, the GPS accuracy specifications indicate (and historical data from F/A-18 tests validate) that when working properly, the HERR should be less than 80 ft the vast majority of the time. Secondly, analyses of F/A-18 flight tests show that aircraft banking or pitching maneuvers tend to cause the GPS measurement errors (including the HERR) to immediately jump to much higher values (i.e., 400 ft), even while the aircraft maintains accurate position. In other words, the HERR does not reflect the true position error for these temporary situations, so the TAWS assigns the position error to grow more slowly (with the INS drift).

Determining Aircraft Altitude And Altitude Error

When the GPS reported vertical error (VERR) is less than 80 ft, the GPS altitude is used for the best MSL altitude parameter. If the VERR is greater than 80 ft, the barometric altitude is used instead, as historical data shows if the VERR is greater than 80 ft, the barometric altitude is likely to be more accurate and should be used instead. In the case where the aircraft enters the transonic region, the last reported "non-transonic" value is used and updated using the inertial damped barometric parameter.

Accurate aircraft altitude is considerably more difficult to determine than position, because of sensor accuracy. Signal Processing keeps track of which MSL sensor is being used, so that adjustments can be made to the height-above-terrain estimate whenever the logic switches among the various choices. Sensory hierarchy is as follows:

GPS Altitude

The GPS altitude value is used when the VERR has been less than 80 ft within the past 50 seconds. If the VERR is acceptable (< 80 ft), the altitude error is set equal to the VERR. When the VERR is greater than 80 ft, the estimate of altitude error is increased by 2 ft/sec only if the INS altitude differs from the GPS altitude by more than the altitude error estimate. This is done so that a spike in bad GPS data will not instantaneously raise the estimate of the altitude error. Instead, it will grow by as much as 100 ft over 50 seconds, and only then if the GPS altitude really is different than the INS BARO altitude.

INS Altitude

The INS BARO altitude is used when INS is valid, and GPS is not valid. First, there is a check to see if the INS altitude differs from the ADC barometric altitude by more than 800 ft, while the aircraft is not in the transonic region. This is done because the F/A-18 has altitude-processing logic, which can add a 900-ft bias to the INS altitude while transonic. This check ensures INS BARO altitude is not used in these conditions. The worst case error specification for

barometric altitude error is 8.3% of altitude, so to estimate the one-sigma error, the larger of 75 ft and one-half of the specification error (4.15%) is used. The altitude error is increased by 2 ft/sec until the error reaches the one-sigma value. However, when the BARO and GPS altitudes agree, the altitude is assumed good and the error estimate will not grow larger.

<u>Barometric Altitude</u>

The lowest priority is the ADC barometric altitude: and is used when both the GPS and INS are not valid.

CFIT PROTECTION

The Protection component of the TAWS determines if ground impact is imminent for the two mutually exclusive warning modes, GEAR and TRAJECTORY. If impact is imminent, the appropriate warning mode is set and the warning is issued. In most cases, CFIT protection is provided by checking the predicted recovery trajectory against the terrain database and determining if the two intersect. When they do intersect, the TRAJECTORY Warning Mode is set until the predicted trajectory no longer intersects the terrain database. When the TAWS is in the FLAT EARTH mode, the terrain database is not used for determining a warning condition. In this case, the TRAJECTORY Warning Mode is set when the altitude required to recover the aircraft is greater than or equal to the current height above the terrain plus a clearance altitude. This is applicable only while over level or descending terrain. No protection into rising terrain is provided while in FLAT EARTH mode.

The TRAJECTORY Warning Mode provides protection by monitoring the altitude required to recover the aircraft and the height above the terrain. Depending upon the sensor validity, availability of DTED, and flight phase, this may be accomplished by projecting the recovery trajectory in three-dimensions and overlaying it on the RDTED database (DTED Terrain

Definition Mode), or comparing the altitude required for recovery to the height above terrain (FLAT EARTH Terrain Definition Mode).

Recovery Trajectories

Within the DTED mode, two recovery trajectories are computed to overlay the RDTED database. The Vertical Recovery Trajectory (VRT) assumes the pilot will roll to wings-level, then apply a longitudinal pull to a constant 5g (or 80% of the aircraft available g if Nz limited). The Oblique Recovery Trajectory (ORT) assumes the pilot will simply apply a longitudinal pull at whatever the current bank angle is. At zero bank angle, the ORT and VRT are identical. The two recovery trajectories are shown in Figure 5-1.

For a warning condition to exist, both calculated trajectories must intersect the terrain in the RDTED database, which helps avoid nuisance warnings. This is especially important in mountainous terrain where the aircrew can see a turn in a valley and intend to maneuver through

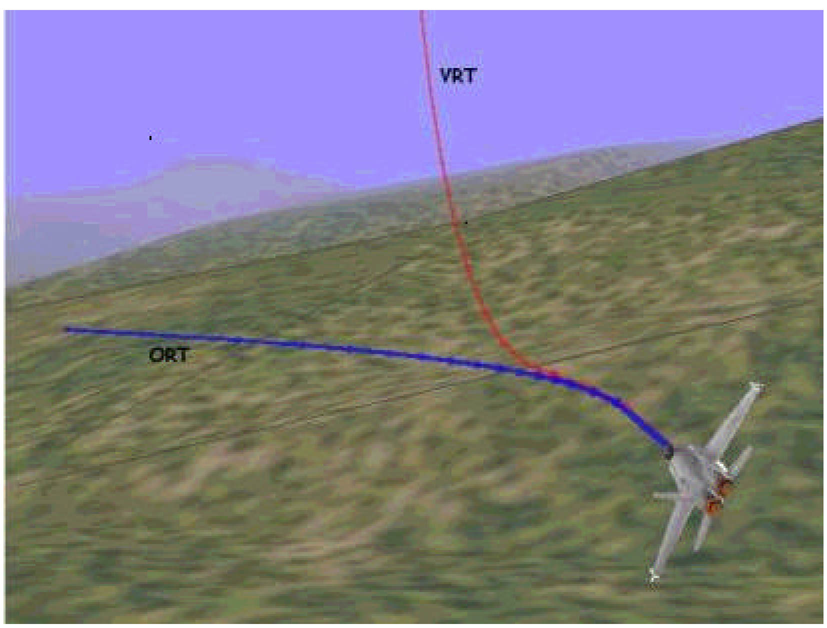


Figure 5-1
VRT and ORT Recovery Trajectories

it, but the VRT detects potential ground impact because of the assumption that the aircraft will roll to wings-level and then pull up. This assumption causes the VRT to intersect the side of the valley that the aircrew is already aware of and maneuvering around. Within the FLAT EARTH mode, the altitude required for recovery is based solely on the altitude lost during the VRT.

Recovery Phases

The recovery is broken into five phases: pilot response, roll response, G delay phase, G-onset phase, and dive phase. The intention is to accurately model both the VRT and ORT in real time according to the aircraft's instantaneous performance capability. In each phase of the recovery (except for the dive phase), the time to complete that phase is computed and used in kinematic equations that define position, velocity, and acceleration.

Pilot response phase

The pilot response phase is the period from when the aircrew receives the warning cues to when the first action is taken to affect the recovery (lateral stick for roll-out, longitudinal stick for pull-up, etc.). This "processing" time is rather short for a pilot with high situational awareness, and longer for a pilot who has lost situational awareness. Simulator and flight test from the GPWS development program showed that a highly aware pilot could react as fast as 0.4 seconds, and an unaware pilot could take 1.0 second or longer.

Predicting the pilot response time is very difficult due to this range in actual responses. While the goal is to protect the unaware pilot, selection of too large a pilot response time leads to nuisance warnings for the aware pilot. Therefore, based on the results of eight years of GPWS development and testing, a pilot response time of 1.3 seconds is used for the TAWS. This value was increased after the first phase of flight test due to the desire to increase protection and because nuisance warnings were non-existent.

Roll Response Phase

The roll response phase is the period from when the aircrew initiates recovery to when the aircraft reaches the calculated target bank angle required to clear terrain. If no roll is required for the recovery (VRT with small bank angle or ORT), the roll response phase will be nonexistent for that frame.

The predicted roll response takes into account the platform-specific performance characteristics. The roll performance characteristics assume that 50% lateral stick is used for initial bank angles less than 70°, and 75% lateral stick for those greater than 70°. These conservative assumptions allow the aircrew to roll faster than designed which may increase the bottom-out altitude.

When the TAWS is in the DTED mode, the roll response phase, as well as the subsequent phases, must be computed twice per frame. The first pass is for the VRT, which assumes a target bank angle of zero. The second pass is for the ORT, which assumes the target bank angle is the bank angle at the end of the pilot response phase.

G Onset Delay Phase

The aircraft now has the lift vector pointing in the desired direction when the aircrew begins pulling to the target normal acceleration. As the pilot applies aft stick, the horizontal stabilizer moves to a more trailing-edge up condition. This causes downward motion of the tail and eventually the nose pitch-up normally associated with the stick deflection. The tail moves downward because the deflection of the horizontal stabilizer creates a downward force. This downward force instantaneously reduces the overall lift the aircraft is generating though it is quickly compensated for by the nose pitching up. The reduction of lift before it increases is seen as a short-term reduction in normal acceleration on the aircraft. This is referred to as a non-minimum phase response and is accounted for in this phase.

In addition, the F/A-18 flight control system also uses a G-limiter to ensure the aircrew does not exceed the structural limit of the airframe. The limit value for the G-limiter is reduced during transonic flight to alleviate overstresses due to the highly dynamic nature of transonic flight. Because TAWS allows for accelerations (and decelerations) during the predicted recovery trajectories, and the change in G-limiter threshold during transonic flight can greatly affect the recovery trajectory, the TAWS must account for this transonic "G-bucket". This means that in addition to the predicted ground and air speeds, the TAWS must predict the mach number at various points of the recovery.

G Onset Phase

The G-onset phase of the recovery is the time from the application of aft stick to the time that the target normal acceleration is achieved. This may be in the vertical plane (VRT) or in an oblique plane (ORT). If the current normal acceleration is greater than or equal to the target, there is no G-onset phase. The target G-onset rate is computed from the airspeed, gross weight, and external stores configuration. This estimate is based upon historical flight test data and an F/A-18 high-fidelity airframe simulation. The assumed recovery technique is ramped aft stick (over 0.75 seconds) sufficient to achieve the target normal acceleration.

Dive Phase

Once the recovery enters the dive phase, the required pilot maneuvering is over. Above approximately corner speed (and for the ORT), the dive phase is assumed a constant normal acceleration constant airspeed maneuver whose trajectory is very closely approximated by an ellipse. Below cornering speed (and for the VRT), the dive phase is assumed to have axial acceleration due to the pilot applying maximum power. This axial acceleration causes an increase in airspeed and therefore an increase in the target normal acceleration for the dive phase (especially notable during slow speed conditions). For the vertical recovery trajectory, the ellipse

is in the vertical plane. For the oblique recovery trajectory, the ellipse is rotated about the flight path in the body axis and about vertical in the inertial axis.

<u>Recovery Trajectory Calculation</u>

The VRT begins at the current aircraft position and ends when the aircraft is climbing vertically. Figure 5-2 shows a VRT broken into its phases.

Fifteen samples are taken along the trajectory and are spaced as:

- 3 samples from the roll phase
- 3 samples from the G-onset phase
- 9 samples from the dive phase at equal intervals in horizontal translation

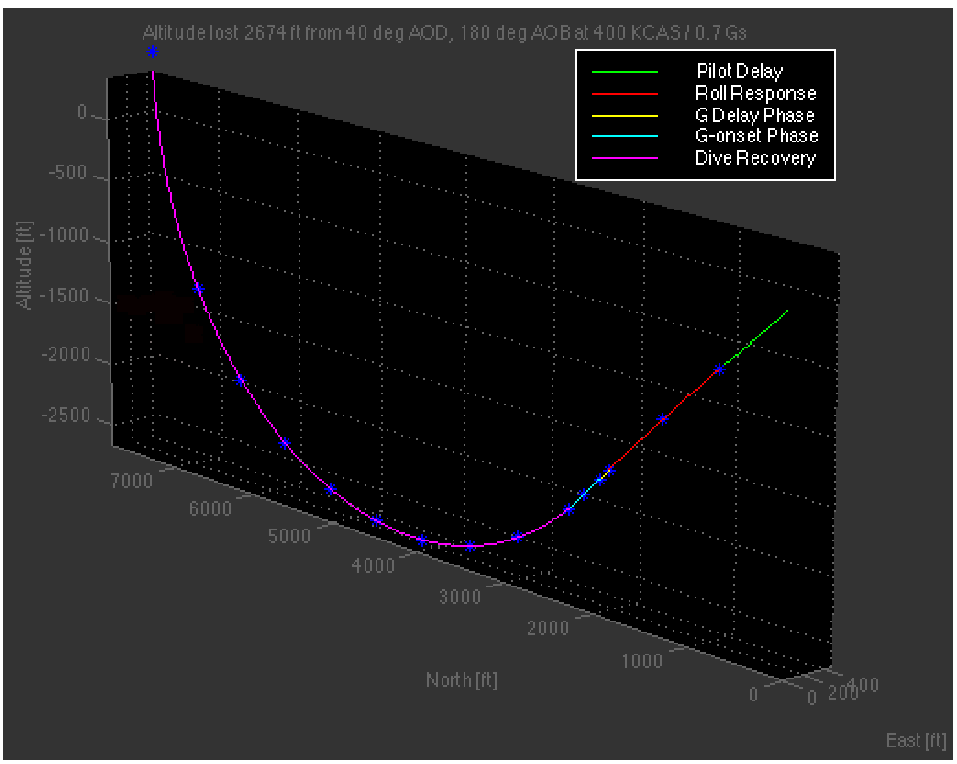


Figure 5-2
Vertical Recovery Trajectory [11]

Fifteen samples are used because in the worst case, the aircraft is capable of traversing fifteen RDTED gridposts during the recovery (15 gridposts = 7380 feet). This division of samples was chosen to reflect phases where the recovery could indeed be completed. That is, due to the pilot response characteristics, a recovery has very little chance of being completed during the pilot response phase. Similarly, the G-delay phase is so short (< 0.5 sec) and bounded by the roll and G-onset phases that it is effectively represented by them.

The oblique recovery trajectory is computed after the VRT computations are complete. The ORT, like the VRT, begins at the current aircraft position, but it ends at different points, depending upon the bank angle. The ORT uses between 10 and 15 samples along the trajectory, shown in Figure 5-3. This is done to avoid nuisance warnings during maneuvers in confined areas such as canyons or below mountain peaks where the ORT may actually predict an intersection behind the turning aircraft. Even though the number of samples used in the terrain intersection computation is variable, fifteen points are still computed along the entire ellipse.

Warning Determination

Once the samples for each recovery trajectory are computed, the terrain elevation at each sample is compared with the predicted aircraft altitude along the trajectory plus the clearance altitude, which in the case of the F/A-18 is 50 ft. Each trajectory sample contains the latitude, longitude and altitude of the aircraft along the trajectory. The latitude and longitude are used to query the DTED database for the elevation at that point. When the terrain elevation returned from the DTED database is greater than or equal to the predicted altitude, a potential warning exists.

When the RDTED terrain elevation exceeds the predicted altitude at any sample, the terrain elevation is also examined at points to the left and right of the intersection point, perpendicular to

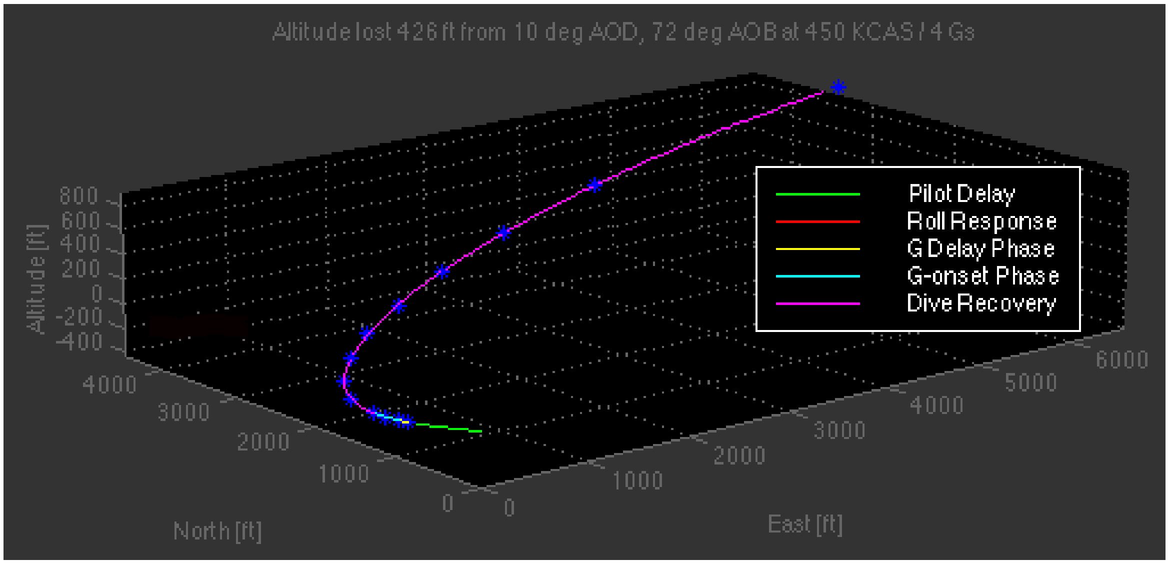


Figure 5-3
Oblique Recovery Trajectory [11]

the trajectory, thus making the trajectory appear like the shape of a “T”. This is done because in mountainous terrain, a potential warning at one latitude/longitude may not require a warning at a different location. Any map registration errors or the potential of aircraft maneuvering during the recovery are accounted for with the “T” when ascertaining that a warning is required. The distance right and left of the trajectory to check is the maximum of the position error and one-eighth of the distance from beginning of trajectory to the intersection point in the horizontal plane. Only when all three terrain elevations are greater than or equal to the trajectory altitude will a potential warning exist.

A TRAJECTORY warning can be set only when both the VRT and ORT are detecting an intercept. Whenever trajectory protection detects an intercept (along the trajectory and "T" for VRT, or along the trajectory for ORT), a persistency counter for the appropriate trajectory is incremented until four consecutive frames of intercept occur. Once one of the persistency counters reaches four, a warning is set as soon as the persistency counter for the "other" trajectory

becomes non-zero. The system thus determines which trajectory describes "the way out" and is conveyed to the aircrew as the directive recovery cue. This is used by the mission computer to determine whether the recovery arrow on the HUD should be ground or aircraft stabilized as described below. Once the TRAJECTORY Warning Mode has been set, it is cleared by four consecutive frames of no intercepts on either trajectory.

When the TAWS is in the FLAT EARTH mode, there is no need to compute the trajectory points as above since no digital terrain data is used for comparison. FLAT EARTH mode requires only the altitude required to arrest the downward velocity to the targeted value. This is determined using the kinematic updates from each phase. The end of the recovery while in the FLAT EARTH mode occurs when the aircraft is parallel to the terrain, and is determined from the terrain slope that is computed in the signal processing component.

Clearance Altitude

The clearance altitude is the designed bottom-out altitude for the recovery. The value of the clearance altitude is based upon whether the TAWS is in the landing phase or not. While in the landing phase, the clearance altitude is the configurable parameter *Landing_Clearance_Altitude*, the altitude at which the target downward velocity is to be achieved during landing. While not in the landing phase, the clearance altitude is *Cruise_Clearance_Altitude*. (The configurable parameters and their values are listed in Table A-2)

TAWS WARNING MECHANIZATION

When the system determines a warning is in order, the mission computers provide both visual and aural warnings to the pilot.

Aural Warnings

The audio cues are intended to be the primary warning cue, and are presented simultaneously with the visual cues. The voice warnings are 3-6 dB above normal cockpit communications with a female voice inflection that communicates the sense of urgency of the situation. Multiple audio warnings will be issued during the recovery if the situation requires. Each audio cue is issued so that the aircrew will hear the entire directive cue, and cannot be interrupted. This is a hardware limitation with the amplifier, control intercommunication (ACI), which generates all F/A-18 audio cueing. The warnings are issued until the warning condition no longer exists.

Aural warnings consist of the following cues:

- "Roll Left, Roll Left"
- "Roll Right, Roll Right"
- "Pull-Up, Pull Up"
- "Power, Power"
- "Check Gear"

Multiple aural cues may be required for a single recovery. For example, most ORT recoveries issue a "Roll Left/Right" followed by "Pull Up".

Visual Cues

The video cueing consists of the "TAWS arrow" presented in the HUD with at least the same intensity as the surrounding HUD symbology. The arrow is 50 mr wide and 150 mr high (for the F/A-18 implementation), drawn around the optical center of the HUD. The arrow has a notch in the bottom so that the direction of the arrow can be ascertained from either the top or bottom. In some cases, the top of the arrow may not be instantaneously visible in the HUD. The arrow remains on the HUD as long as the Warning Mode is set.

There are two orientations for the arrow in the HUD, set according to the commanded recovery trajectory. For the Vertical Recovery Trajectory, the arrow will be presented perpendicular to the horizon; that is, pointing "up" in the inertial coordinate system, as shown in Figure 5-4 where the aircraft is shown rolled 45 deg left.

For the Oblique Recovery Trajectory, the arrow will remain fixed to the aircraft's Z-axis pointing "up", as shown in Figure 5-5. The orientation of the arrow is dependent upon the parameter desired recovery path determined by the TAWS algorithm.

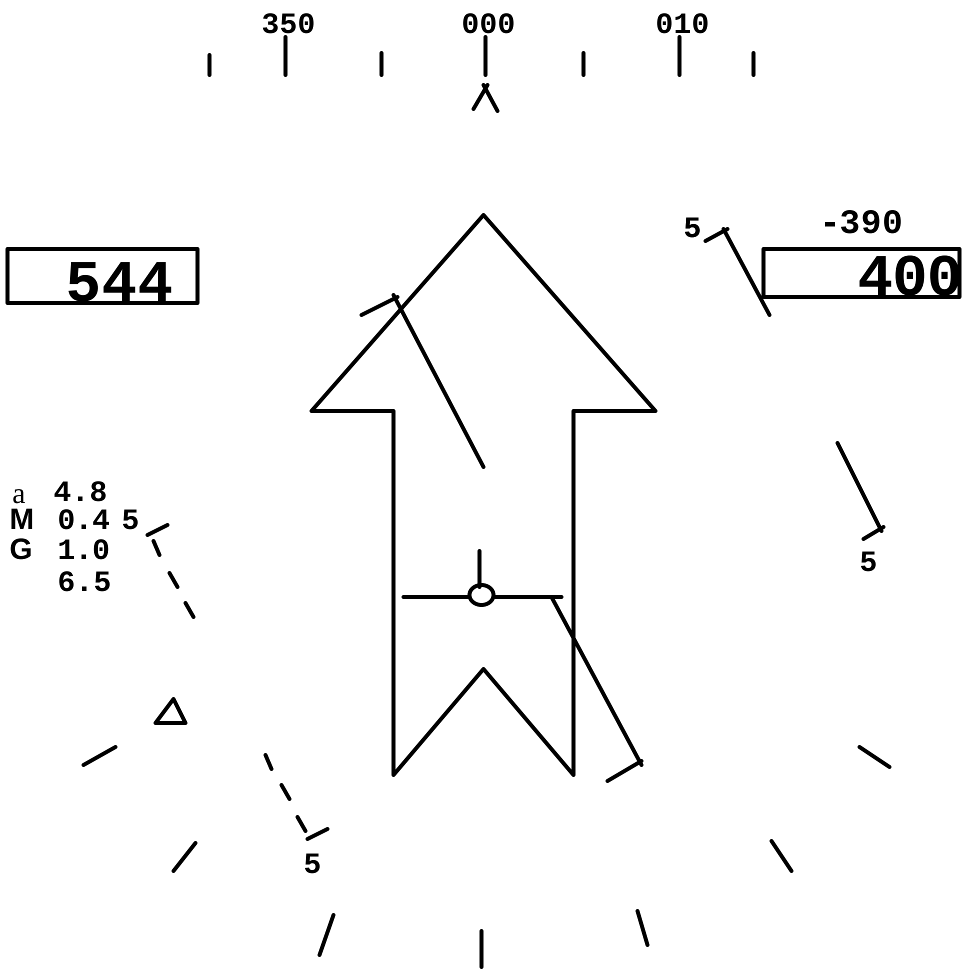


Figure 5-4
HUD Indications for Vertical Recovery Trajectory

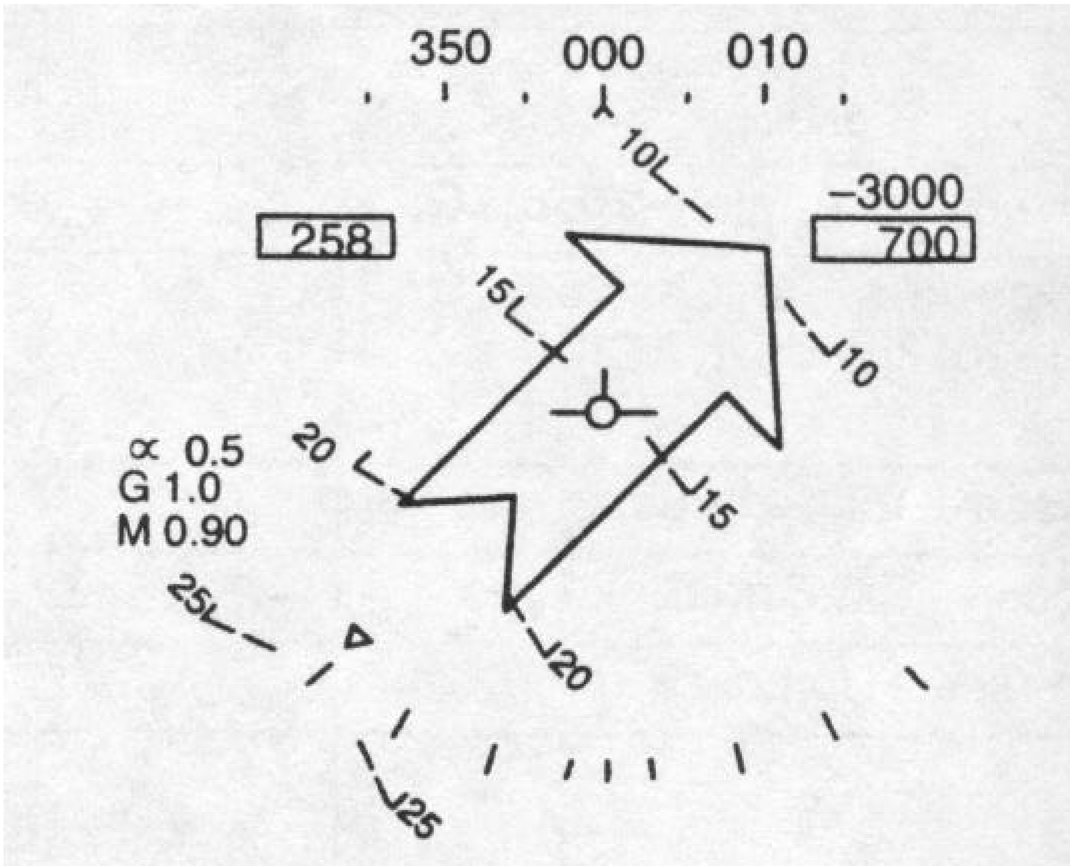


Figure 5-5
HUDIndications for ORT Recovery

6. FLIGHT TESTING TAWS ON THE F/A-18

Just as the maneuvering envelope and mission requirements define the system design for terrain warning systems on military aircraft, the requirements for testing such a system are likewise expanded when compared with those intended for commercial aircraft. Flight testing the TAWS system recently developed for the F/A-18 provides an example.

BACKGROUND

Development of the F/A-18 TAWS system required a large number of tests to validate the approach and assumptions inherent in the system design. Numerous simulation events were required to tweak the algorithms to provide the maximum amount of protection while minimizing nuisance warnings. Flight testing was also required to validate that the system did not provide nuisance warnings while the aircraft was operating in it intended environment performing tactically relevant missions.

The TAWS test effort was undertaken as an integrated system test involving multiple test techniques using both simulation and flight tests. Complementary use of simulation and flight test using altitude safety buffers and a host of risk mitigations was the key to developing a robust safety system that minimizes nuisance warnings. The objectives of the flight test program are summarized in Table 6-1.

Flight testing was carried out in several phases with both F/A-18C/D and E/F variant aircraft, which are aerodynamically very different, in order to verify that the configurable parameters were optimized for each. Two categories of flight testing were required: performance flight testing and nuisance cue testing. Since TAWS was designed to be a last-ditch safety system, it obviously could not be flight tested safely in its intended operating environment. Because of this, a number

Table 6-1
F/A-18 TAWS Test Requirements and Evaluation Criteria [10]

REQUIREMENT	TESTS	CRITERIA
Ensure warning cues appear at the design thresholds/time	Pilot maneuvers aircraft to generate terrain closure, excessive sink rate, excessive bank angle, floor altitude and gear up warnings. Recover aircraft. Exercise mode transitions.	Warnings/transitions as designed.
Ensure trajectory components and bottom out altitudes.	Pilot maneuvers aircraft into trajectory warning. Upon receipt of aural/visual cues, pilot executes recovery.	Actual vs. computed warning altitude within greater of either: 10% of trajectory altitude or 100 ft.
Ensure that the number of nuisance cues has been minimized	Normal fleet operations which approach warning boundaries: • Low level flight operations • Simulated weapons delivery at minimum altitudes • LAT • Off nominal approaches • VFR approaches, etc.	Nuisance Cues: less than 8% of the intended maneuvers/events. For Low level flight operations 1 minute of flight equals 1 event. P_{nw} less than 8% (threshold) P_{nw} less than 3% (objective)
Ensure that assumed parameters are sufficient to prevent CFIT following loss of Situational Awareness (SA). Investigate pilot response, roll out, G-onset, sustained G, and bottom out altitude.	Test pilot closes his eyes to simulate loss of SA; aircraft is then maneuvered into simulated CFIT situation by the safety pilot. Test pilot initiates recovery at warning.	P_{sw} greater than 60% (threshold) P_{sw} greater than 90% (objective)
Test for false cues caused by spurious signals (data spikes, wingman, power interruptions, etc.)	All flight tests and formation flight.	No false cues.

of special techniques were developed to safely conduct flight test while measuring system performance to the maximum extent possible.

UNIQUE SAFETY PRECAUTIONS

Because of the nature of this flight testing, there was a considerable amount of attention given to planning the profiles. The desire to test as close to the ground as possible for accurate aircraft performance and pilot perception needed to be delicately balanced with the required altitude buffer in order to ensure safety. Some unique methods were developed to provide as much margin for safety as possible, while fulfilling the flight test requirements.

Flight Test Safety Buffer Altitude

The aircraft mission computer software was modified to allow the use of a temporary false floor altitude that raised the perceived terrain elevation above the real terrain, allowing flight test to be conducted farther from the ground. When the aircraft was configured for flight test, the pilot was presented with an option to enter a buffer altitude between 0 and 12,700 feet . This buffer is then subtracted from the TAWS final height above terrain parameter and MSL altitudes used in all warning calculations. This buffer did not change the indicated altitude presented to the pilot, or the responses of the aircraft low-altitude warning system which is composed of an MSL altitude warning setting and the radar altimeter (RADALT) warning setting.

Each time the buffer was enabled or the altitude setting changed, the buffer check procedure was performed to verify that it was working properly. This involved descending at approximately 300 fpm to verify the warning at 50 ft above the false floor altitude. The 300 fpm was used to standardize the procedure at a descent rate low enough so that the warning would not appear higher than the minimum 50 ft warning provided when a slow descent toward the ground was occurring. (Higher descent rates would move the warning higher.) The buffer check flight test card is presented in Figure 6-1.

Profile Planning

All dive profiles were planned using the Aircraft Target Area Maneuvering Simulation (ATAMS) weaponeering program using worst-case aircraft gross weight and test conditions. Tolerances for dive angle and airspeed were defined, and using the worst case of all parameters that contribute, the expected altitude loss was calculated for every event. The ATAMS altitudes were used because they are slightly more conservative than those derived from the TACMAN dive recovery charts.

The expected altitude lost was used to determine the "terminate run altitude" which was the minimum altitude allowable to ensure the aircraft recovered above the "bottom out altitude." Table 6-2 shows the bottom out altitudes that were used, which differed as a function of dive angle.

Using the terminate run altitude and minimum bottom out altitude, the required buffer altitude could be determined so that the expected TAWS warning could be forced away from the terrain for testing. Buffer altitudes were chosen so that there was ample time during the dive for the expected TAWS warning to be given and the recovery started prior to the terminate run altitude. Figure 6-2 shows the relationship between the various altitude parameters.

Safety Observers and Displays

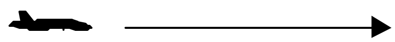
Even though the safety altitudes were defined, it was determined that the test team needed to monitor the altitudes and other safety critical parameters to be prepared to make knock-it-off calls at the terminate run altitude if the TAWS system failed to provide warnings. The test team was

Table 6-2
Minimum Dive Recovery Bottom Out Altitudes

DIVE ANGLE (Degrees)	BOTTOM OUT ALTITUDE (ft)
0-9	500
10-19	1000
20-37	2000
38-50	3000

Flight Event: 214/107 ***F/A-18 Advanced Weapons Lab*** Flight Date: 12/20/0

Buffer Setting/Check



5,200 AGL
300 ± 30
KCAS
0° ± 10° AOB

MSTR MODE: **NAV** MSTR ARM: **SAFE** WPN:	HUD
VIDEO: HUD VTR 1 · LCAM VTR 2 · LCAM VTR 3 · LCAM VTX	Software Altitude Warnings BARO: 8,100 RDR: 0

1. Set Safety Buffer:
   Unit 28
   Address **21016**
   Data **11754** (5,100 ft)
2. Set RALT **min**

3. Set Baro 8,100

3. Descend at 300 fpm

4. __ Verify "Pull-Up, Pull-Up" at **5,150** ft AGL

5. Perform G-Warm

Next: Warmup 1
13,200 ft MSL / 200 KCAS

E/F TAWS **1**

Figure 6-1
Flight Test Buffer Check Card

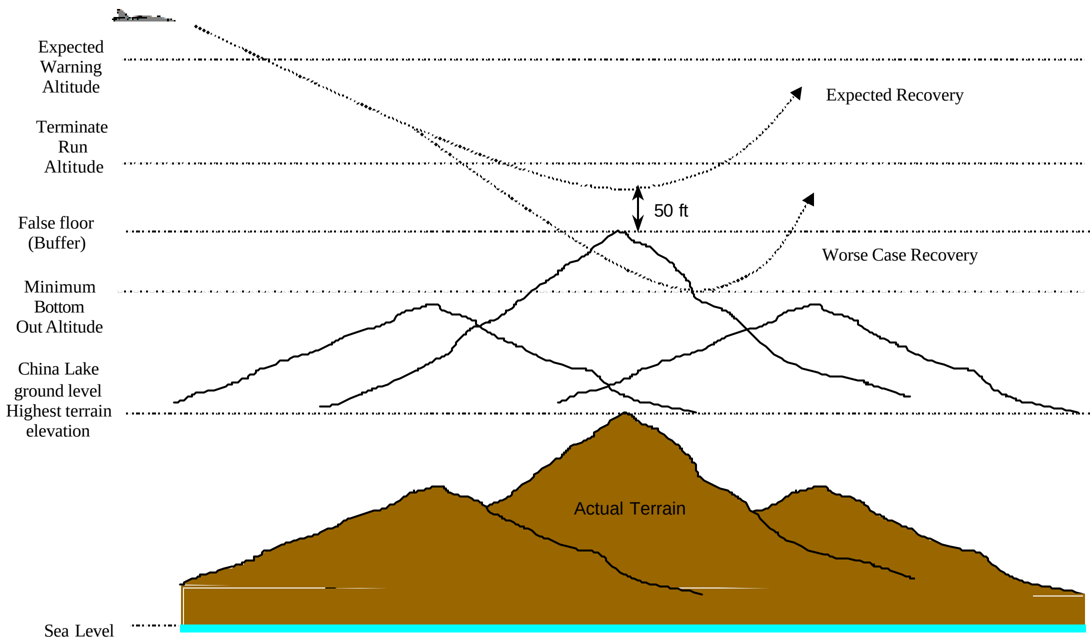


Figure 6-2
Safety Altitude Parameter Definitions [10]

organized with a safety observer and the test conductor monitoring displays in the control room to provide an independent abort call if required during each run.

Telemetry Data System

To do this, a number of aircraft parameters had to be telemetered to the ground. The standard flight test telemetry (TM) system on the F/A-18 test aircraft was capable of monitoring all of the required parameters, and sending them to the China Lake Range Control Center (RCC) bays in real time. The required parameters are listed in Table 6-3.

In addition, it was determined that the test team should use an alternate altitude source to make the abort determination in case the altitude sensors aboard the aircraft (which were of course also used as inputs to the TAWS system) should provide inaccurate data. For this reason, the aircraft was configured with an Advanced Range Data System (ARDS) pod, which uses differential GPS to determine precise Time/Space/Position Information (TSPI) and relayed it to the RCC bays.

Safety Displays

Because of the very dynamic nature of the safety data, a determination was made to design some special displays to show the required information graphically in order to ensure that it was evaluated correctly during each event. For the CFIT protection flights, a graphical display was developed which plotted altitude and dive angle against a template showing the dive angle tolerances and terminate run altitude, so that it was relatively easy to determine if the aircraft was outside the envelope which determined the altitude lost during recovery. A sample display is shown in Figure 6-3. Note that the altitude is shown as AGL altitude. As mentioned, an independent altitude source was used to drive the safety display, however, the ARDS pod provided only MSL altitude, which was converted to worst case AGL altitude by assuming a suitable terrain height. The highest terrain in the range area was used, which resulted in a

Table 6-3
Required Real-Time Data Parameters [10]

Critical Test Parameters	Critical Safety Parameters
Airspeeds (VCAL, VTRUE)	Airspeeds (VCAL, VTRUE)
Dive Angle	Dive Angle
Radar Altitude	Altitude (ft AGL)
Baro Altitude	Normal Acceleration (N_z (G))
TSPI Altitude	Mach Number
Vertical Velocity	Angle of Attack
Bank Angle	
Stick position	
TSPI Lat/Long	
Hot Mike to RCC	

conservative estimate of actual aircraft AGL altitude, depending on the terrain below. The dive angle data was taken from the aircraft telemetry stream. Several other similar displays were developed for use during nuisance warning testing, where no altitude buffer was used. The Low-Altitude Tactics (LAT) display is shown in Figure 6-4.

LAT maneuvers were performed over level ground, so the known terrain elevation was used in conjunction with the ARDS altitude data to provide accurate AGL altitude for use on the display without resorting to aircraft derived data. This provided for an extra measure of protection with accuracy that supported the desire to test to a minimum altitude of 200 ft.

A similar display, shown in Figure 6-5 was used for weapons delivery profile nuisance warning testing.

Safety Pilot

The use of a back-seat safety pilot was mandated for some of the testing, to ensure that if the primary pilot were to be disoriented, there would be some means of recovering the aircraft. This was particularly important for the "closed eyes" CFIT testing where the front seat pilot was deliberately disoriented to evaluate the recovery performance of the system when the pilot had

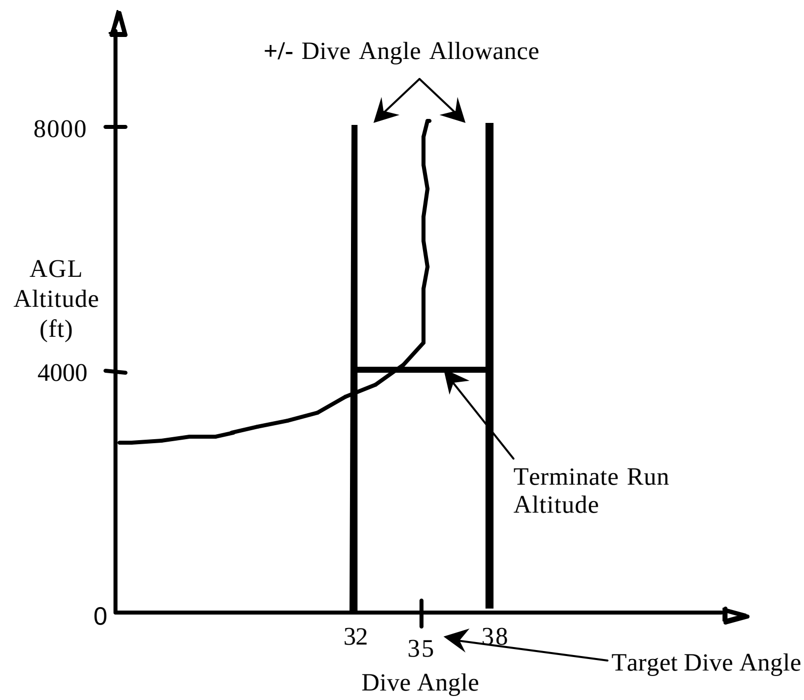
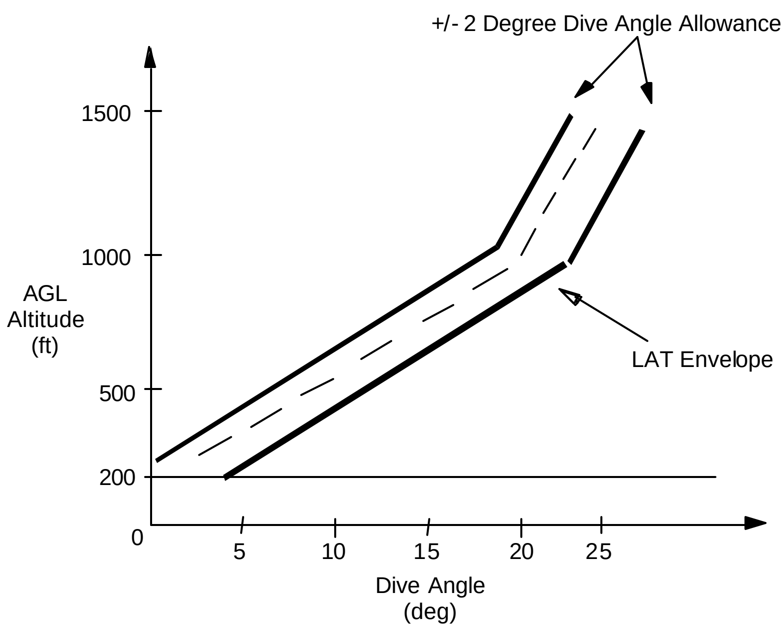


Figure 6-3
CFIT Protection Flight Test Safety Display



NAVY LAT DIVE RECOVERY RULES	
DIVE ANGLE	**ALTITUDE**
25	1500
20	1000
15	750
10	500
5	250

400 - 525 KTAS

Figure 6-4
LAT Dive Recovery Safety Display

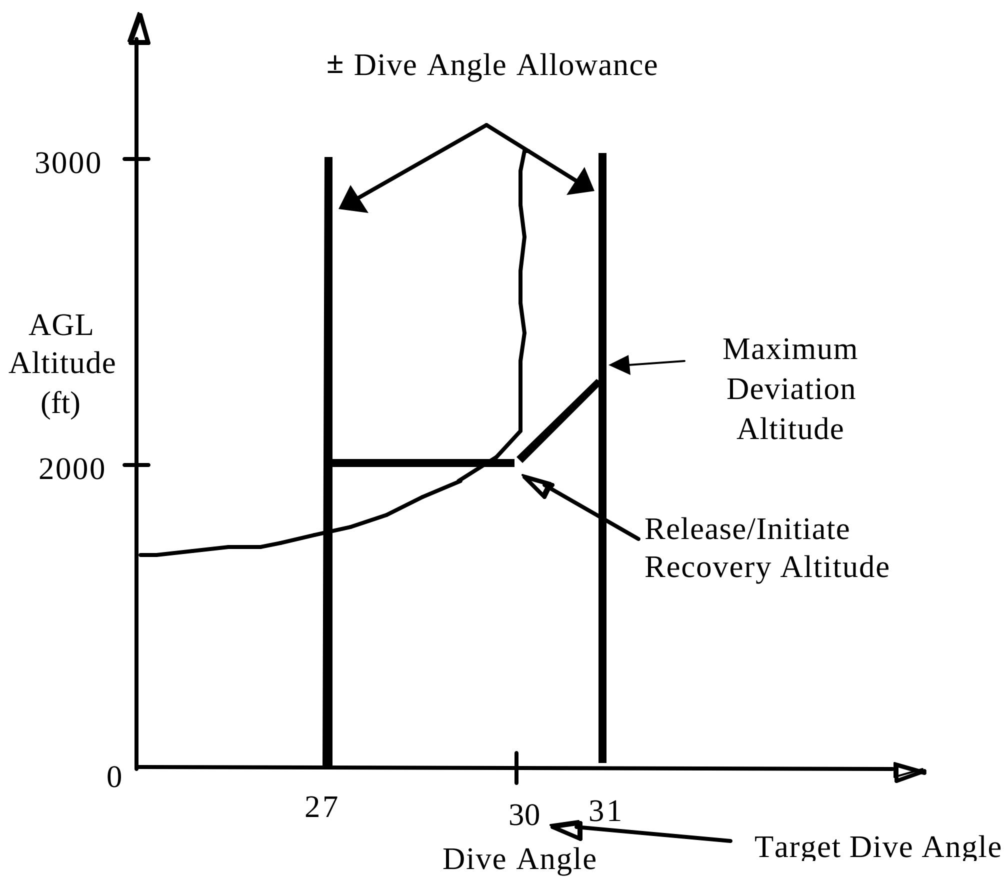


Figure 6-5
Weapons Delivery Profile Safety Display

suffered a loss of situational awareness – a primary reason for implementing the TAWS system. The primary test aircraft was configured in the "trainer configuration" with flight controls in both the front and aft cockpits.

Simulator Requirements

In addition to the heavy use of the Manned Flight Simulator for algorithm development, the simulator was used to pre-fly all test points. It was deemed a safety requirement that all aircrew develop and maintain proficiency for TAWS testing prior to actual flight test events. This also helped develop the starting points for some of the more difficult scenarios, which were very dependent on technique used to get the aircraft to the required point in the sky with the proper attitude and airspeed desired. Table 6-4 summarizes the simulator requirements for both primary Test Pilot and Safety Pilot for the different events.

ADDITIONAL SAFETY PRECAUTIONS

In addition, a number of common flight test "best practices" were used in combination to assure maximum safety. The concept of "build-up" was applied, which dictated that the events be done in a particular order with the functional flights flown first. This also drove the desire to flight test at higher altitudes before moving the profiles either faster or lower. Likewise, practice events and those with lower g-onset rates were flown first.

Also, the Naval Air Systems Command Test Hazard Analysis process was applied to all aspects of this flight test program to identify, categorize and attempt to mitigate all identified risks. Each identified risk was mitigated in some way, and then the residual risk was assessed for severity and probability in order to categorize the remaining risk. The residual risk matrix is presented in Table 6-5.

Table 6-4
Pilot/Flight Simulator Proficiency Requirements [10]

Flight	MFS flight	Practice Flight
Functional Test	Required within 45 days prior to functional test flight.	None required.
Low level [1]	None required.	None required.
LAT Test pilot [2]	Required within 30 days prior to LAT practice flight.[6]	Required within 14 days prior to LAT test flight.[6]
LAT Safety pilot [3]	Required within 30 days prior to LAT practice flight.[6]	Back or front seat practice flight required within 14 days prior to LAT test flight. [4,6]
CFIT Test pilot [7]	Required within 45 days prior to CFIT test flight.	None required.
CFIT Safety pilot [7]	Required within 45 days prior to CFIT test flight.	None required.
Simulated Weapon Delivery profiles	Required within 45 days prior to weapons test flight.	None required.
Off Nominal Approaches [5]	None required	None required.

Notes:
1. Must have flown 500 ft low level test flight prior to 200 ft (same route).
2. Must have been F/A-18 LAT qualified.
3. Must have previously completed a LAT instructor course.
4. Must have flown 500 ft or lower low level within 14 days prior to LAT practice flight.
5. LSO required
6. Must have flown within 7 days prior to flying LAT.
7. Refresher required within 15 days of test flight.

The complete Test Hazard Analysis for the F/A-18 TAWS test program is listed in appendix B. The overall flight test category was assessed as Category B, which determined the level of oversight and test team qualifications.

Another standard flight test practice that was used was the use of chase aircraft. This was mandated for some flights, in order to provide an external appraisal of potential dangerous attitude trends while in the low-level environment. This was primarily used for the LAT nuisance testing, and is representative of fleet training practice.

The aforementioned test techniques and practices were all implemented in order to minimize risk. The following sections describe the flight tests in detail as well as the test techniques used to ensure safety.

SYSTEM PERFORMANCE TESTING

Performance flight tests were segregated into three types, and conducted in accordance with logical build-up for a developmental system.

Functional Warning Verification

The first phase of flight test was dedicated to verification of basic system functionality. The flight test safety buffer altitude (discussed in a later section) was verified, an evaluation of aircraft positioning and DTED accuracy was performed, as well as a verification of the graceful degradation of the system when DTED data was invalid or position information was limited. After basic warning functionality was verified by diving towards the ground (with safety buffer), the forward looking capability of the system was evaluated. This was done by picking a terrain feature on the range with abrupt sides and flying directly toward it to verify warnings. Figure 6-6 shows the terrain feature used (renamed “TAWS Mountain” by the test team).

These tests were conducted using several profiles with the aircraft RADALT both on and off, with the aircraft configured in a “light” configuration with only a center-line external fuel tank

Table 6-5
Residual Risk Matrix

Mishap Probability	**Hazard Severity**			
	I **Catastrophic**	**II** **Critical**	**III** **Marginal**	**IV** **Negligible**
A - Frequent	UA	UA	Risk Category C	Risk Category B
B - Probable	UA	Risk Category C	Risk Category C	Risk Category A
C - Occasional	(Note 1)	Risk Category C	Risk Category B	Risk Category A
D - Remote	(Note 2)	(Note 2)	Risk Category A	Risk Category A

Notes:

1. The determination of a test project whose residual risk assessment falls under I/C will require up front discussions with TCT prior to proceeding with the test program development.
2. Assignment of Risk Category where residual risk falls under I/D or II/D will require up front discussions with the TCT to determine whether Risk Category A or B is applicable.
3. UA - Unacceptable risk, project residual risk too high to proceed.
4. Risk Category C - Test or activities which present a significant risk to personnel, equipment or property, even after all precautionary/corrective actions are taken.
5. Risk Category B - Test or activities which present a greater risk to personnel, equipment or property than normal operations.
6. Risk Category A - Test or activities which present no greater risk than normal operations.

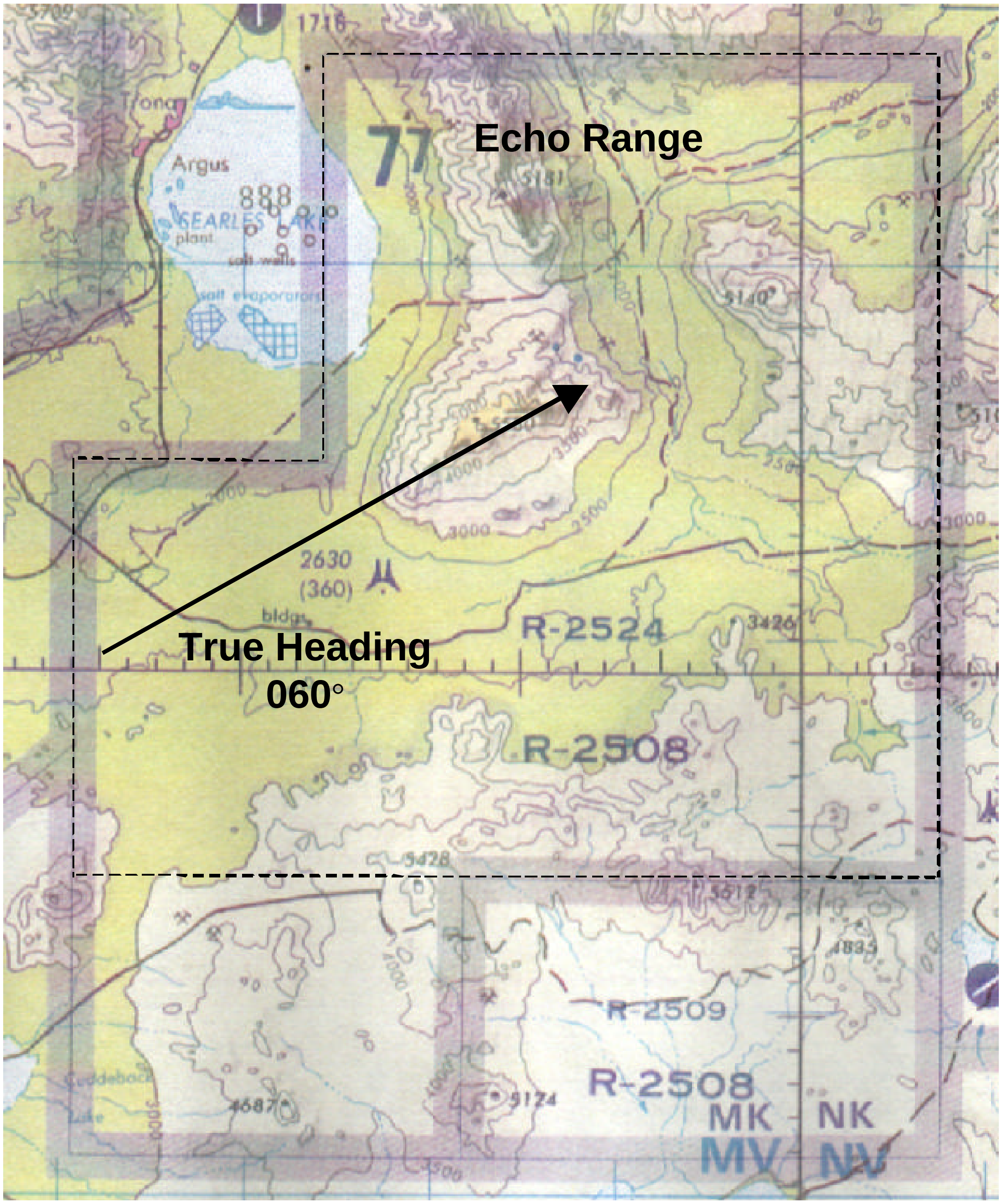


Figure 6-6
Forward Looking Analysis Testing Terrain Feature

and wingtip ARDS pods. The first was a level approach to the mountain using a 1,000 ft buffer as depicted in Figure 6-7. (The peak was at 5,600 ft MSL)

Second was a diving approach to the mountain shown in Figure 6-8. This was also performed with the RADALT both on and off. The points marked "B" and "C" were the terminate run altitude and planned bottom out altitude respectively.

The third scenario was a climbing approach to the terrain feature. This was conducted only with the aircraft RADALT on and is shown in Figure 6-9.

CFIT Protection

The next phase of testing was the CFIT protection evaluation of the system, and was the most dynamic. This involved maneuvering the aircraft toward terrain at varying rates to determine the accuracy of the warnings and terrain clearance during the recovery. This was done with a variety of safety buffer altitudes over level and mountainous terrain with the aircraft configured in one of three ways. A baseline configuration named, "Fighter Escort – Clean" (FE/CL) and a high gross

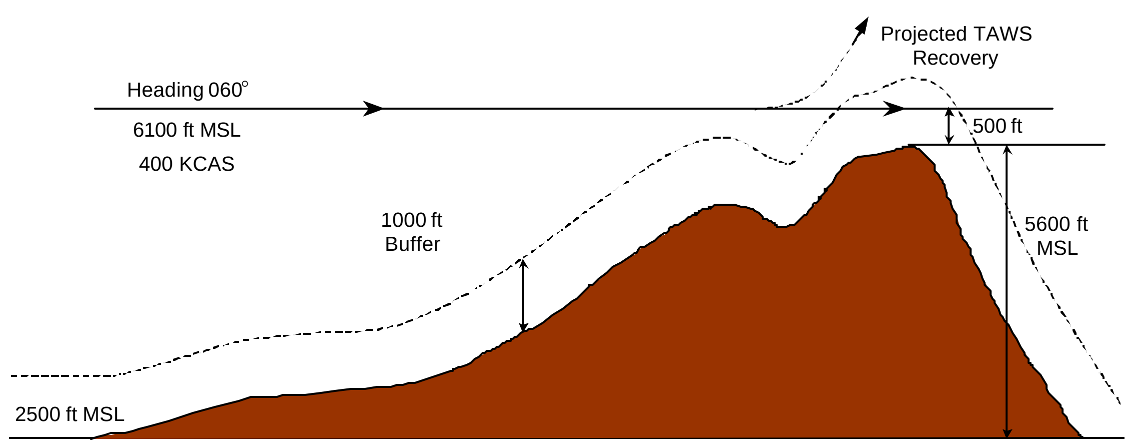


Figure 6-7
Level Approach Forward Looking Analysis

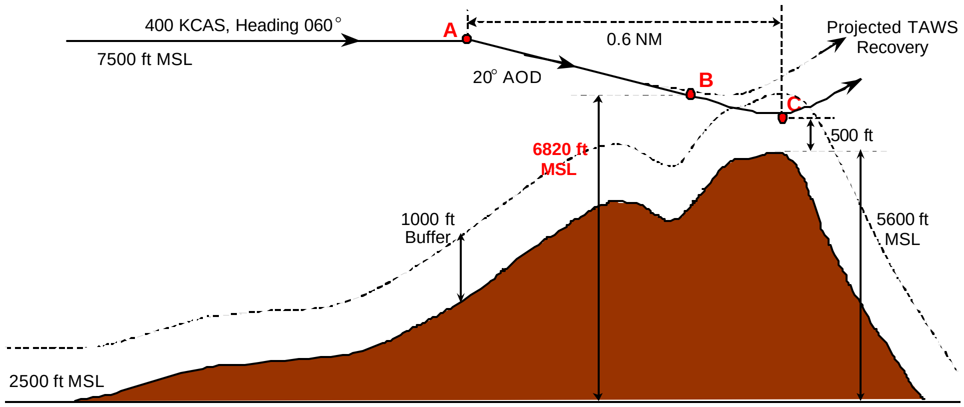


Figure 6-8
Diving Approach Forward Looking Analysis

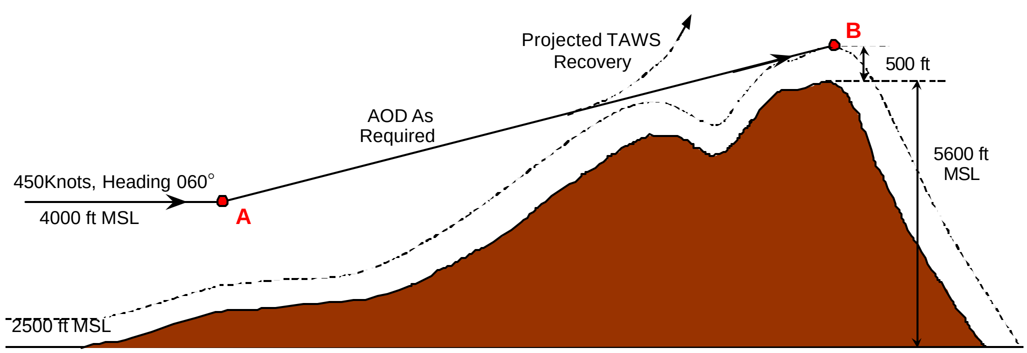


Figure 6-9
Climbing Approach Forward Looking Analysis

weight configuration called the "interdiction" (INT) load were used for most tests to verify the edges of the system performance envelope. In addition, an asymmetric load ("ASYM") was defined to verify the algorithm's accuracy when the aircraft's roll rate and roll limiter were invoked due to an asymmetric configuration. The CR or "Cruise Configuration", which consisted of gear up and flaps in "auto", was used for most testing, although the "Power Approach" (PA) Configuration of gear down with flaps fully extended was used to test landing pattern scenarios. The F/A-18E/F aircraft external stores stations are depicted in Figure 6-10, and the external stores loads are presented in Table 6-6.

CFIT protection flights utilized a "Test Pilot" in the front cockpit, and a "Safety Pilot" at the controls in the back cockpit. To thoroughly evaluate the entire system, the effects of a disoriented pilot needed to be included in the recovery. To do this, each run began with the Safety Pilot maneuvering the aircraft into the point, while the Test Pilot turned his head, closed his eyes and performed some mental task during the setup to induce a loss of situational awareness. When the TAWS aural warning occurred, the Test Pilot reacted to the warning and recovered the aircraft as if his life depended on it. The entire Test Pilot response and recovery, including the initial reaction, g-onset rate, roll rate and intuitive nature of the recovery cues (i.e. did the Test Pilot follow the arrow for the recovery while trying to regain SA?), was evaluated. In the instances

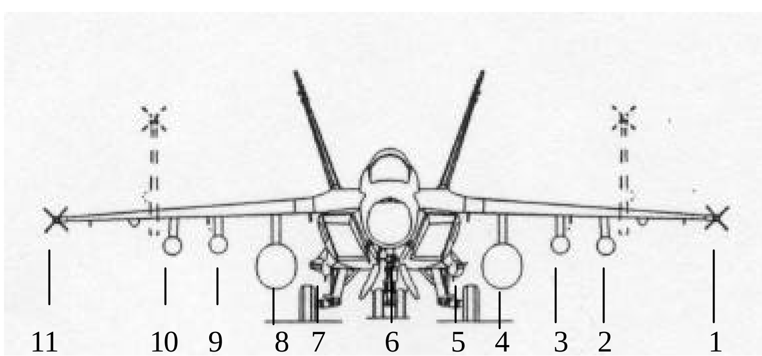


Figure 6-10
F/A-18E/F External Stores Stations

Table 6-6
F/A-18E/F TEST LOADINGS

Loading (Weight)	Station 1	Station 2	Station 3	Station 4	Station 5	Station 6	Station 7	Station 8	Station 9	Station 10	Station 11
FE-CL (53,495 lbs)	ARDS POD				CATM-120	TANK	CATM-120				ARDS POD
INT (61,500 lbs)	ARDS POD		MK84 LDCFA	MK84 LDCFA	CATM-120	TANK	CATM-120	MK84 LDCFA	MK84 LDCFA		ARDS POD
ASYM 22K ft-lbs RWH (54,787 lbs)	ARDS POD		MK84 LDCFA			TANK					ARDS POD

where a "crash" occurred, and the aircraft flew below the buffer altitude, the data were used to re-stimulate the simulator to understand where algorithm adjustments were required.

The Safety Pilot was prepared to take control of the aircraft if the Test Pilot reacted incorrectly to the warning cues, or initiated a recovery at the terminate run altitude if no warning was generated.

In addition, practice runs with the Test Pilot's eyes open were conducted for the most aggressive runs in order to mitigate risk. This allowed the aircrew to become familiar with the g-onset required to avoid aircraft overstress during testing.

CFIT Protection Over Level Terrain

CFIT flights over level terrain were conducted with both FE/CL and INT loadings with test conditions ranging from 150 KCAS to transonic (0.92 IMN) airspeeds, aircraft attitudes of level to 120° AOB, and dive angles between level and 45° at the warning point. Each loading required a different test setup in terms of safety buffer altitudes because of the changes to aircraft performance caused by the differences in gross weight and drag. A summary of the test points and their safety buffer altitudes are shown in Tables 6-7 and 6-8.

CFIT Protection Over Mountains

Testing over varied terrain provided some additional challenges to the test team because of the assumptions that needed to be made to implement the safety buffers. The safety buffers and subsequent altitude calculations for terminate run altitude and expected warnings relied on knowing the actual ground level below the aircraft. Over mountainous terrain the worst case (highest local terrain feature) had to be assumed for safety. Therefore, if the aircraft was not over this terrain feature during the setup, warnings would not be triggered at the expected altitudes, and the terminate run altitude would be penetrated causing a knock it off call by the safety observer. To mitigate this, the buffer altitudes had to be moved up to allow some "slop" to account for this while still providing the required worst case safety independent of terrain.

Due to the varied terrain, it was also determined that these tests should be performed with the Test Pilot's eyes open using only the FE/CL stores configuration. Actual performance of the entire system was extrapolated using the pilot response information gathered while testing over level terrain. Likewise, aircraft performance at the heavy gross weight configuration was verified sufficiently over level terrain. Figure 6-11 shows the actual terrain used for testing, with the highest terrain elevation noted. Table 6-9 shows the list of test points and their associated buffer altitudes.

Asymmetric Dive Recoveries

A subset of the CFIT dive recoveries was tested with the ASYM external stores configuration, which resulted in asymmetry near the aircraft limit. The test was conducted over level terrain with the Test Pilot's eyes open. Risk mitigations included build-up consisting of practice runs at stepped up altitudes and before the PA configuration test as well as the safety observers and displays located in the control room. Table 6-10 depicts the buffer and planned event altitudes for each test point.

Table 6-7
CFIT Over Level Terrain Events – FE/CL Loading

Run	Config	Airspeed ± 20 (KCAS)	Dive Angle (deg)	AOB ± 5 (deg)	Warning Altitude[1] (ft MSL)	Flight Test Safety Buffer Altitude (ft)	Planned Bottom-out Altitude (ft AGL)	Terminate Run Altitude (ft MSL)
F5.P1	CR	250	5 ± 2	0	7586	5100	5150	2982
F5.P2	CR	550	25 ± 2	0	9118	5100	5150	6258
F5.1	CR	550	40 ± 4	40L	11322	5100	5150	9786
F5.2	CR	450	30 ± 5	120L	8884	3700	3750	7862
F5.3	CR	450	35 ± 3	30L	8265	3700	3750	7161
F5.4	CR	550	25 ± 2	0	7718	3700	3750	6258
F5.5	CR	250	30 ± 5	120L	6983	3000	3050	6230
F5.6	CR	350	30 ± 3	20R	6616	3000	3050	5858
F5.7	CR	450	20 ± 2	0	6312	3000	3050	5450
F5.8	CR	250	20 ± 2	30R	5465	2500	2550	5110
F5.9	CR	250	20 ± 4	80R	5912	2500	2550	5577
F5.10	CR	350	10 ± 3	60L	4441	1600	1650	3989
F5.11	CR	450	10 ± 3	80R	4501	1600	1650	4110
F5.12	CR	450	5 ± 2	0	4191	1600	1650	3147
F5.13	CR	450	5 ± 2	30R	4163	1600	1650	3182
F5.14	CR	250	5 ± 2	0	4086	1600	1650	2982
F5.P3[3]	PA	150[2]	15 ± 2	0	4498	1600	1650	4029
F5.15[3]	PA	210	5 ± 2	30R	4101	1600	1650	3024
F5.16[3]	PA	150[2]	15 ± 2	0	4498	1600	1650	4029

Notes:
1. Calculated for a 53,500 lb aircraft and the lesser of 5 G or 80% of available G recovery.
2. Airspeed not less than on-speed AOA.
3. 2G and maximum landing weight (50,600 lb)

Table 6-8
CFIT Over Level Terrain Events – INT Loading

Run	Config	Airspeed ± 20 (KCAS)	Dive Angle (deg)	AOB ± 5 (deg)	Warning Altitude[1] (ft MSL)	Flight Test Safety Buffer Altitude (ft)	Planned Bottom-out Altitude (ft AGL)	Terminate Run Altitude (ft MSL)
F6.P1	CR	250	5 ± 2	0	7588	5100	5150	2992
F6.P2	CR	550	25 ± 2	0	9198	5100	5150	6357
F6.1	CR	550	40 ± 4	40L	11521	5100	5150	10022
F6.2	CR	450	30 ± 5	120L	9279	4000	4050	7992
F6.3	CR	450	35 ± 3	30L	8679	4000	4050	7293
F6.4	CR	550	25 ± 2	0	8098	4000	4050	6357
F6.5	CR	250	30 ± 5	120L	7088	3000	3050	6342
F6.6	CR	350	30 ± 3	20R	6669	3000	3050	5929
F6.7	CR	450	20 ± 2	0	6347	3000	3050	5497
F6.8	CR	250	20 ± 2	30R	6012	3000	3050	5157
F6.9	CR	250	20 ± 4	80R	6480	3000	3050	5650
F6.10	CR	350	10 ± 3	60L	4447	1600	1650	4001
F6.11	CR	450	10 ± 3	80R	4505	1600	1650	4118
F6.12	CR	450	5 ± 2	0	4194	1600	1650	3155
F6.13	CR	450	5 ± 2	30R	4165	1600	1650	3187
F6.14	CR	250	5 ± 2	0	4088	1600	1650	2992
F6.P2[3]	PA	150[2]	15 ± 2	0	4498	1600	1650	4095
F6.15[3]	PA	210	5 ± 2	30R	4110	1600	1650	3031
F6.16[3]	PA	150[2]	15 ± 2	0	4498	1600	1650	4095

Notes: 1. Calculated for a 61,000 lb aircraft and the lesser of 5 G or 80% of available G recovery.

2. Airspeed not less than on-speed AOA.
3. 2G and maximum landing weight (50,600 lb)

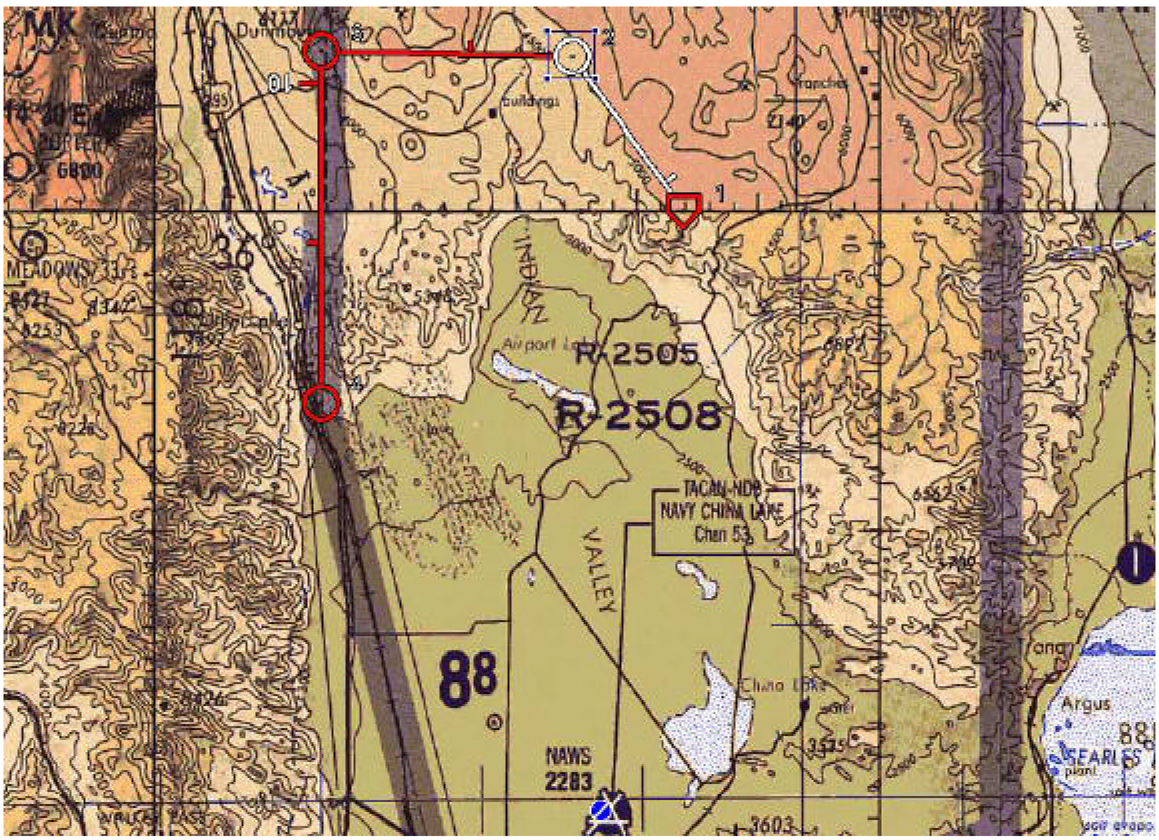


Figure 6-11
CFIT Over Mountainous Terrain Test Area

Table 6-9
CFIT Over Mountainous Terrain Test Points

Run	Config	Airspeed ± 20 (KCAS)	Dive Angle (deg)	AOB ± 5 (deg)	Warning Altitude[1,4] (ft MSL)	Flight Test Safety Buffer Altitude[4] (ft)	Planned Bottom-out Altitude[4] (ft AGL)	Terminate Run Altitude[4] (ft MSL)
F4.P1	CR	250	20 ± 2	0	11040	5100	5150	7968
F4.P2	CR	550	40 ± 4	0	14023	5100	5150	12392
F4.1	CR	550	40 ± 4	0	14023	5100	5150	12392
F4.2	CR	450	35 ± 3	0	10987	3500	3550	9836
F4.3	CR	450	20 ± 2	30L	9938	3500	3550	8767
F4.4	CR	450	30 ± 4	80R	11290	3500	3550	10325
F4.5	CR	550	20 ± 3	50L	10560	3500	3550	9463
F4.6	CR	350	30 ± 4	60R	10350	3500	3550	9205
F4.7	CR	250	20 ± 2	0	9440	3500	3550	7968
F4.8	CR	450	10 ± 4	120L	7910	1600	1650	7643
F4.9	CR	250	10 ± 4	120R	7648	1600	1650	7182
F4.10	CR	350	10 ± 2	20L	7335	1600	1650	6787
F4.11	CR	550	10 ± 2	0	7507	1600	1650	7005
F4.12	CR	550	10 ± 2	40L	7695	1600	1650	7263
F4.13	CR	250	10 ± 4	80R	7612	1600	1650	7149
F4.14	CR	250	5 ± 2	30R	7149	1600	1650	6085
F4.P3[3]	PA	150[2]	15 ± 2	30R	7515	1600	1650	7172
F4.15[3]	PA	190	5 ± 2	0	7145	1600	1650	6039
F4.16[3]	PA	150[2]	15 ± 2	30R	7515	1600	1650	7172

Note: 1. Calculated for a 53,500 lb aircraft and the lesser of 5 G or 80% of available G recovery.
2. Airspeed not less than on-speed AOA.
3. 2G and maximum landing weight (50,600 lb)
4. All altitudes based on highest local terrain elevation of 5348 feet MSL.

Nuisance Warning testing

The final phase of testing was nuisance warning evaluation. The system design made trade-offs in performance to reduce nuisance warnings as much as possible because of prior experience with GPWS, which initially was prone to nuisance warnings. To verify this, a series of tests were flown to probe the edges of the aircraft operating envelope. No buffer altitudes or other limitations were imposed on the aircraft for these flights.

Low-Level Performance

Two nuisance warning low-level routes were developed and flown to ensure that tactically representative maneuvers made during low-level flight would not result in warnings. These routes included mountainous terrain, ridgeline crossings, canyons and flight over water. They were flown with both the FE/CL and INT loads, first at 500 ft and then at 200 ft. Safety mitigations included buildup, and a chase aircraft for the 200 ft evaluation. The routes were flown at 450 – 540 KCAS. Figure 6-12 details one of the two routes within the R2508 restricted area.

Low Altitude Tactics

Another potential source of nuisance warnings was the standard maneuvers and dive angle rules that make up Low Altitude Tactics (LAT). These are Three Dimensional (3D) evasive maneuvers that are flown to within 200 ft of the ground in strict accordance with a set of rules that detail dive angle and altitude. The test team used the safety displays detailed earlier and a safety observer in the control room to provide a knock-it-off call if required. These standard maneuvers were flown with a LAT qualified Test Pilot and LAT instructor Safety Pilot in the back seat. All points were flown first in the simulator, and several proficiency flights were flown to gain LAT currency prior to the flight tests. LAT dive rule recovery points are shown in Table 6-11.

Table 6-10
Asymmetric Dive Recovery Test Points

Run	Config	Airspeed ± 20 (KCAS)	Dive Angle (deg)	AOB ± 5 (deg)	Warning Altitude (ft AGL)	Flight Test Safety Buffer Altitude (ft)	Planned Bottom-out Altitude (ft AGL)	Terminate Run Altitude (ft AGL)
S14.P1.1	CR	550	40 ± 4	40L	9764	6200	6250	7300
S14.1.1	CR	550	40 ± 4	40L	8764	5200	5250	7300
S14.1.2	CR	450	30 ± 5	120L	6196	3600	3650	5200
S14.1.3	CR	250	30 ± 5	120L	4679	2900	2950	4000
S14.1.4	CR	450	20 ± 2	0	3819	2900	2950	3100
S14.1.5	CR	250	20 ± 2	30R	3620	2900	2950	2900
S14.1.6	CR	350	10 ± 3	60L	1979	1400	1450	1700
S14.P1.7	PA	210	5 ± 2	30R	1631	1400	1450	800
S14.1.7	PA	210	5 ± 2	30R	931	700	750	800

Notes: 1. Calculated for a 61,000 lb aircraft and the lesser of 5 G or 80% of available G recovery.
2. Airspeed not less than on-speed AOA.

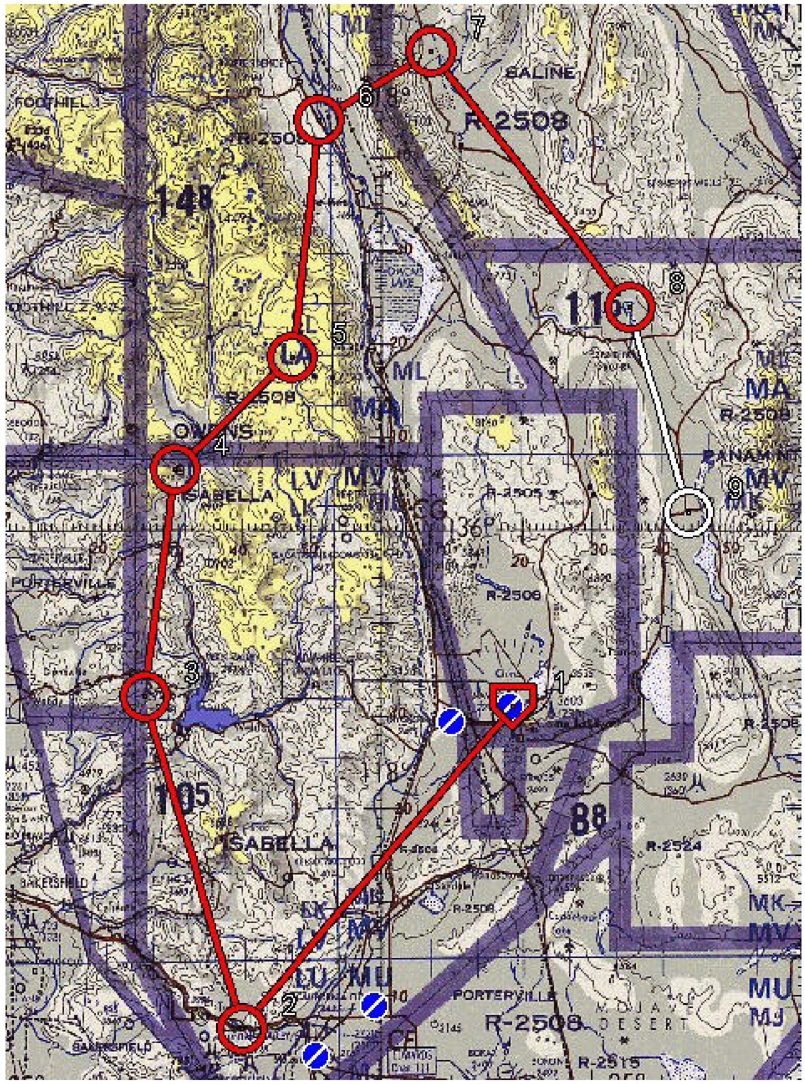


Figure 6-12
TAWS Low-Level Nuisance Route

The 3D LAT maneuvers consisted of the Straight-ahead Oblique Jink (SOJ), Vertical Jink, Reverse Oblique Jink (ROJ), and Turning Oblique Jink (TOJ), as listed in Table 6-12, which details the test points and bottom-out altitudes.

Weapons Delivery Recovery Testing

Some weapons delivery profiles at the edges of the aircraft performance envelope were also flown to check for possible nuisance warnings. While no weapons were released, these were performed with the heavy INT loadout and were conducted on the range with the test team safety observers and displays. All points were flown in the simulator first, and buildup was applied by flying the fastest point at each dive angle at stepped up altitudes prior to lowering the profile to the minimum altitude. The altitude lost during these "warmup" delivery profiles was compared with the predictions before moving down. The "Z-Diagrams" detailing the dive delivery parameters are presented as Figure 6-13. Recovery was initiated at the release altitude or the aircraft "Break-X" (a HUD bombing mode symbol which indicates the weapon has insufficient

Table 6-11
LAT Dive Rule Recovery Test Points

Run	KCAS	Dive Recovery			Bottom-out Altitude
		Dive	AOB	Altitude	
F12.2.1	420	10	0	500	200
F12.2.2	480	10	0	500	200
F12.2.3	520	10	0	500	200
F12.2.4	420	25	0	1500	200
F12.2.5	480	25	0	1500	200
F12.2.6	520	25	0	1500	200
F12.2.7	420	20	0	1000	200
F12.2.8	480	20	0	1000	200
F12.2.9	520	20	0	1000	200

Table 6-12
3D LAT maneuvers

Run	Dive Recovery			Bottom-out Altitude
	Maneuver	**Climb Angle (deg.)**	**Delay (sec)**	
F12.3.1	SOJ	20	0	200
F12.3.2	Vert Jink	20	0	200
F12.3.3	ROJ	20	0	200
F12.3.4	TOJ	20	0	200
F12.3.5	SOJ	25	0	200
F12.3.6	Vert Jink	25	0	200
F12.3.7	ROJ	25	0	200
F12.3.8	TOJ	25	0	200

time to properly arm) whichever comes first. No buffer altitudes were used.

Off-Nominal Approaches

The final nuisance warning check was during simulated off-nominal carrier landing approaches. While a primary designed use for the system includes providing protection around the carrier landing pattern, there was some concern that warnings might be given in off-nominal, but not CFIT imminent conditions. Therefore several series of approaches was designed which included final corrections near the touchdown point to see whether warnings would be triggered. These tests were run under the control of a Landing Signal Officer (LSO) just as they would be during a carrier landing, but were performed at China Lake rather than at an actual aircraft carrier. The LSO acted as the safety observer, ready to call a wave-off if adverse trends were noted during testing. Tables 6-13 and 6-14 summarize the approach and landing points tested.

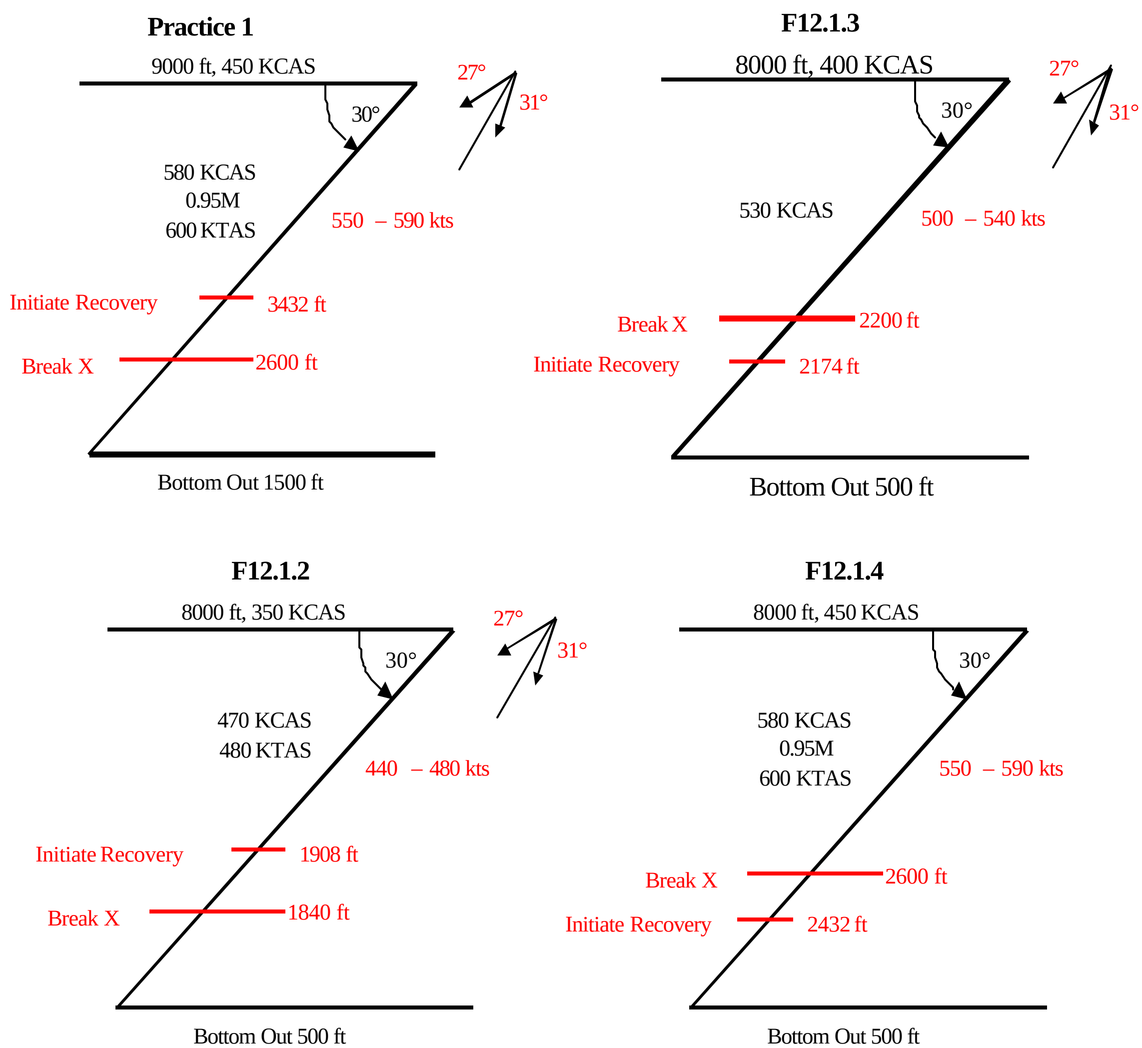


Figure 6-13
Weapons Delivery Nuisance Warning Test Dive Profiles

Table 6-13
Off-Nominal Approach and Landing Scenarios

Approach #	Pass
F13.2.1	VFR approach,400 KCAS 1000 foot break at numbers, tight pattern, flared, Touch-and-Go
F13.2.2	VFR approach, simulate IFR approach, break out at 200 feet, high on centerline over end of runway, flare, Touch-and-Go, repeat as required.
F13.2.3	VFR approach, 400 KCAS 1500 foot break at numbers, tight pattern, flare, Touch-and-Go.
F13.2.4	VFR approach, simulate IFR approach, break out at 200 feet, high over end of runway and 200 feet right of centerline, descend to runway and flare, Touch-and-Go, Repeat as required.

Table 6-14
Off –Nominal Carrier Landing Scenarios

Approach #	Pass	LSO notes
	Nominal pass.	OK
F13.1.1	1 ball high start, correct to on glideslope by in the middle position	HX HCDIM
F13.1.2	2 ball high start, correct to on glideslope by in the middle position	HX HCDIM
F13.1.3	1 ball high from start to in the middle, correct to on glideslope by in close position	HX-IM HCDIC
F13.1.4	High overshooting start, 2 ball high overshooting start, correcting to on glideslope and on line up by in the middle	HOSX CD•LUIM

7. CONCLUSIONS AND RECOMMENDATIONS

Flight testing terrain warning systems intended for use on high performance aircraft presents many unique challenges due to the required operating envelope and basic assumptions made in their design. There is usually very little margin allowed for recovery once a warning is issued, and testing such systems thoroughly and safely can be extraordinarily difficult.
As discussed in the previous section, some particular techniques can be employed to both safely and thoroughly test such systems.

First, some means of elevating the testing away from the true terrain must be used if the system is designed to provide last second warnings that would be too hazardous to test without sensible terrain clearance factors. The use of a designed-in capability for "tricking" the system into adding a safety buffer to calculated results while still using aircraft sensor inputs should be considered.

The use of simulation to extend test results can provide a means of affordably testing a system safely throughout an aircraft's operating envelope. Though the cost of developing and validating the models using carefully constructed flight tests can be expensive, it is cost effective when considering the cost of repeated flights in a fly-fix-fly scenario which is often required to optimize protection algorithms and minimize nuisance warnings. In addition, simulation scenarios that are unsafe to fly can be run to test system operation to the extreme edges of the aircraft operating envelope. It is recommended that simulation models be developed and validated for use in testing terrain avoidance systems.

Since terrain warning systems rely on aircraft sensors to provide inputs, considerable risk is generated by using those sensor to provide safety information during flight test. A single sensor malfunction could result in failure to initiate a timely recovery. In addition, test pilot task saturation or fixation can also result in failure to recover from test maneuvers near terrain. These risks can be mitigated by instrumenting test aircraft with redundant sensors, as well as telemetry

systems to relay appropriate data to dedicated safety monitors that can focus solely on issuing backup recovery initiation calls if required.

In addition, thorough testing of terrain avoidance systems intended for high-performance aircraft would require an inordinate number of flights to cover all of the possible permutations of aircraft configuration, external stores asymmetry and maneuver envelopes possible for modern multi-mission aircraft. A worst-case set of configurations should be defined to maintain confidence that the system will work as expected throughout its intended operating envelope.

Also, the nature of terrain avoidance system testing, where most events need to occur in proximity to terrain, introduces some unusual risks into a planned test program. Close attention to detail and a very rigorous safety review process must be utilized to ensure that nothing is overlooked, and that the planned events are safe.

Table 7-1 summarizes the recommendations for conducting safe and effective flight tests of terrain avoidance systems intended for use on high performance aircraft.

Table 7-1
Summary of Recommendations

	Recommendation
1	Design a system safety buffer to move testing away from terrain
2	Simulation models must be validated and used to verify proper warning generation at the edges of the protection envelope and to optimize CFIT protection versus nuisance warnings.
3	Instrument the test aircraft with telemetry for use in providing dedicated safety displays on the ground for backup recovery calls.
4	Worst case gross weight, asymmetry and operational scenarios should be developed to spot check system operation throughout the aircraft operating envelope for all mission areas.
5	A rigorous safety review process should be utilized to ensure safety when developing test scenarios

REFERENCES

REFERENCES

1. Bateman, D., "CFIT Accident Statistics", Honeywell International, August 2000.

2. "Terrain Awareness and Warning System (TAWS) Mandate Final Rule"; FAA Amendment No. 91-263; 121-273; 135-75; 29 March 2001.

3. "Investigation of Controlled Flight Into Terrain", Volpe National Transportation Systems Center, DOT-TSC-FA6D1-96-03, March 1996.

4. Stiff, J. S., "Analysis of Controlled Flight Into Terrain Incidents Involving U.S. Naval and Air Force Tactical Aircraft (1979 – 1989), Naval Weapons Center TP7132, March 1991.

5. "Minimum Performance Standards-Airborne Ground Proximity Warning Equipment", Radio Technical Commission for Aeronautics (RTCA) DO-161A, 27 May 1976.

6. "Technical Standard Order – Terrain Awareness and Warning System", TSO-C151a, U.S. Federal Aviation Administration, 29 Nov 1999.

7. Airworthiness Criteria for the Installation Approval of a Terrain Awareness and Warning System (TAWS); FAA Advisory Circular AC 25-23; 22 May 2000.

8. Combley, J.R. (The Boeing Company), "Ground Proximity Warning System Testing", Proceedings of the Sixth Annual Symposium, Society of Flight Test Engineers, 1975, p. 159-178

9. Anderson, T.E., "Embedded Terrain Awareness Warning System V1.8 Software Design Description", Naval Air Warfare Center Aircraft Division, 19 October 2001.

10. Bayer, LCDR A. J. and G. D. Glen, "TAWS F/A-18 Developmental Flight Test Plan", C00-12-405B0, dated 31 Oct 00.

11. Air Test and Evaluation Squadron Three One Standard Operating Procedures, dated 16 Oct 00.

APPENDICES

APPENDIX A

Table A-1
F/A-18 TAWS Configurable Parameters

Array OffSet	Parameter Name	Description	F-18CD value	F-18EF value
0	Aircraft_Type	Determines which aircraft TAWS is in	2	1
1	Bank_Threshold	Threshold for when "close enough" to Ending_Roll	30	30
2	Cruise_Clearance_Altitude	Targeted bottom-out altitude	50	50
3	Data_Invalid_Threshold	Maximum number of invalid DTED points	5	5
4	Default_Weight	Fail safe gross weight value - used when weight is available	30000	40000
5	Gear_Structural_Limit	Landing gear sink rate structural limit	24.8	26.4
6	Landing_Altitude_Threshold	Maximum altitude for landing profile	500	500
7	Landing_Clearance_Altitude	Targeted altitude for structural gear limit	10	10
8	Maximum_G	Maximum value for target normal acceleration	5	5
9	PA_Lift_Coefficient	Lift coefficient for landing profile	1.5	1.55
10	Pilot_Delay_Time	Basic pilot reaction time	1	1
11	Reference_Weight	Reference weight for G-limiter	32357	42097
12	Roll_Mode_Constant	Roll mode time constant	0.5	0.5
13	UA_Lift_Coefficient	Lift coefficient for cruise profile	1.7078	1.8
14	Wing_Area	Wing area for lift computation	400	500
15	Dyn_Press_Threshold	Threshold for switching between PA & UA	202	195
16	Landing_Airspeed_Threshold	Maximum airspeed for landing profile	200	200
17	Close_to_ground	Minimum value for believable DTED_HAT	10	10
18	DTED_Bad_K	Value for DTED_Error when DTED is invalid	299	299
19	DTED_Bad_value	Value for terrain height when DTED is invalid	-32767	-32767
20	First_DTED_Error	Initial value for DTED Error	10	10
21	First_Sigma_P	Initial value for Sigma P	5	5
22	First_terrain_variation	Initial value for terrain variations	5	5
23	I_am_lost	Maximum value to believe current aircraft position	500	500
24	I_am_REALLY_lost	Maximum value to believe aircraft position when over the ocean	5000	5000
25	Lowest_Max_DTED_Error	Minimum value for Max_DTED_Error	120	120
26	Max_under_ground	Value used when checking if the aircraft is below the DTED terrain	50	50
27	MSL_Error_Divisor	MSL Error divisor for calculating DTED error	20	20
28	Sigma_Mult_for_Max_Error	How many standard deviations is Maximum error?	4	4
29	Terrain_Exponent	Exponent for terrain height used to determine DTED error	0.25	0.25
30	Terrain_Multiplier	Factor for multiplying terrain variation to	2	2

Table A-1 (Continued)
F/A-18 TAWS Configurable Parameters

Array OffSet	Parameter Name	Description	F-18CD value	F-18EF value
		determine DTED error		
31	Terrain_Quality_Index	Conversion of terrian variation to equivalent of sigma_P	0.25	0.25
32	Terrain_Variation_K	Decay divisor for calculating terrain variation	15000	15000
33	Max_Error_K	Value for Maximum DTED Error when DTED is invalid	99999	99999
34	Accuracy_Exponent	Weighting for 1 frame of Rad_Alt data	3	3
35	Diff_BW_Neighbor_divisor	Proportion of Diff_BW_Neighbor to add to Final_HAT	2	2
36	Long_Bias_decay	Constant to determine speed of decay for Long_Bias	0.998	0.998
37	Long_Bias_divisor	Constant to determine how much 1 frame contributes to the Long_Bias	200000	200000
38	Nuisance_K	Weighting of buffer "noise" to add to Final_HAT	1.0	1.0
39	Rad_Error_K	Constant to determine part of Rad_Alt_Error used for noise buffer	0.5	0.5
40	Short_Bias_decay	Constant to determine speed of decay for Short_Bias	0.90	0.90
41	Short_Bias_divisor	Constant to determine how much 1 frame contributes to the Short_Bias	5000	5000
42	S_b_divisor	Proportion of Short_Bias used to derive noise in Final_HAT	4	4
43	Inhibit_Timer_Threshold	Threshold value for inhibit timer to indicate timeout	11	11
44	Baro_Bias	F/A-18 bias put into INS Baro in some transonic conditions	800	800
45	Baro_Error_Multiplier	Estimated error in BARO altitude based on spec	0.042	0.042
46	First_MSL_Error_Est	Initial value for MSL Altitude error	50	50
47	GPS_Alt_Error_Max	Altitude error limit for using GPS data	80	80
48	GPS_Pos_Error_Max	Position error limit for using GPS data	80	80
49	Lower_transonic	Beginning of transonic mach region	0.95	0.95
50	Position_Drift_Timer	Time of how long after loss of GPS we lose position fix	500	500
51	Upper_transonic	End of transonic mach region	1.05	1.05
52	Aural_Persistence_Timer_Threshold	Threshold value for aural persistence timer to indicate timeout	4	4
53	Gear_Repetition_Time	Repetition t ime for "Check Gear" when gear handle is down	80	80
54	Latch_Timer_Bank_Threshold	Bank threshold value for latch timer	45	45
55	Latch_Timer_Threshold	Threshold value for latch timer to indicate timeout	20	20
56	Left_Bank_Threshold	Threshold to determine left/right roll command	150	150
57	PA_Power_Threshold	Criteria for using "Power" during landings	8.5	8.5
58	Throttle_Threshold	Threshold to determine when at full power	100	46.5
59	UA_Power_Threshold	Criteria for using "Power" during cruise	18	18
60	Enough_bad_hits	Number of bad data points needed to disable Over_Ocean	500	500

Table A-1 (Continued)
F/A-18 TAWS Configurable Parameters

Array OffSet	Parameter Name	Description	F-18CD value	F-18EF value
61	Exponent_for_Rad_Alt_angle	Increase in error due to platform not level	3	3
62	Need_consecutive_hits	How many good consecutive rad alt readings needed for persistency timer	3	3
63	Ocean_Check_MSL_Multiplier	Multiplier for potential error when verifying no terrain over the ocean	2	2
64	Proportion_of_sigma_P	Additional error from terrain roughness ahead	50	50
65	Rad_Alt_multiplier	Proportional radar altimeter error	0.005	0.005
66	Starting_Rad_Alt_K	Constant radar altimeter error	2	2
67	Minimum_good_Rad_Alt_HAT	Minimum value to believe Rad_Alt with DTED	40	40
68	First_Pos_Error	Initial value for Position_Error	100	100
69	Points_to_Use	How far ahead to look in DTED to calculate Sigma_P	15	15
70	Under_the_Earth	Lower-than-possible value for DTED terrain height	-1000	-1000
71	Coast_Altitude_Threshold	Altitude below which COAST should transition to OPERATE	4000	4000
72	Envelope_Timer_Threshold	Threshold value for envelope timer to ignore the radar altimeter	40	40
73	Ignore_Radalt_Altitude_Threshold	Altitude above which the Radar Altimeter may be ignored if not locked on the ground	5000	5000
74	Level_Terrain_Time_Threshold	Time threshold of level terrain	40	40
75	Maximum_Coast_Timer	Timeout value for the Coast timer	1200	1200
76	Maximum_Envelope_Timer	Maximum value for the envelope timer for ignoring the radar altimeter	110	110
77	Maximum_Ignore_Timer	Maximum value for the ignore timer for radar altitude	100	100
78	Maximum_Radar_Altitude	Maximum radar altitude that can be believed	4950	4950
79	Minimum_Radar_Altitude	Radar altitude which is always ignored when above the Ignore_Radalt_Altitude_Threshold	10	10
80	Over_Ocean_Elevation_Threshold	Terrain elevation threshold for non-DTED over ocean determination	100	100
81	Over_Ocean_Slope_Threshold	Terrain slope threshold for non-DTED over ocean determination	1	1
82	Slope_Airspeed_Threshold	Airspeed above which terrain slope can be computed	170	170
83	Terrain_Elevation_Timer_Threshold	Time threshold for erroneous COAST terrain elevations	41	41
84	Gear_Altitude_Threshold	Altitude below which gear protection is provided	150	150
85	Takeoff_Timer_Threshold	Threshold value for takeoff timer to indicate timeout	600	600
86	Waveoff_Airspeed_Threshold	Airspeed below which wave-off can be sensed	200	200
87	Waveoff_Altitude_Threshold	Altitude below which wave-off can be sensed	500	500
88	Waveoff_Sink_Rate_Threshold	Sink rate required for wave-off	-16.67	-16.67
89	Waveoff_Timer_Threshold	Threshold value for wave-off timer to indicate timeout	50	50

Table A-1 (Continued)
F/A-18 TAWS Configurable Parameters

Array OffSet	Parameter Name	Description	F-18CD value	F-18EF value
90	Weight_Off_Wheels_Timer_Threshold	Threshold value for weight-off-wheels time to indicate timeout	60	60
91	Terrain Slope Level Threshold	Threshold which defines level terrain slope for COAST transition	2	2
92	Maximum_Gonset	Maximum Gonset rate during normal operations	5	5
93	Minimum_Gonset	Minimum Gonset rate	0.15	0.15
94	Maximum_Gonset_Nuisance	Maximum Gonset Rate in nuisance prone areas	6	6
95	Radar_Altitude_Jump_In_Threshold	Radar altitude which, when below, is ignored	500	500
96	Maximum_Radalt_Con_Timer	Maximum value for the Radalt Consistency timer	10	10
97	Radalt_Consistency_Threshold	Time threshold for consistent radalt data	6	6
98	Maximum_Terrain_Timer	Maximum value for the Calc_terrain_timer	10	10
99	Maximum_Roll_Time	Maximum value for Roll_Time	4	4
100	Long_Bias_Multiplier_for_DTED	Long bias effect on DTED_Error	2	2
101	Min_Baro_Error	Minimum value for barometric altitude error	75	75
102	ORT_Bank_Angle_Max	Threshold for bank angle to allow upward lift for ORT	72	72
103	ORT_Bank_Cos_Max	Threshold for cos(bank angle) to allow upward lift for ORT	0.3	0.3
104	Avail_Thrust_Con	Constant value for available thrust determination	19177.7	32012.41
105	Avail_Thrust_M1	Coefficient for first order mach term in thrust determination	14745.2	-26821.5
106	Avail_Thrust_M2	Coefficient for second order mach term in thrust determination	0	62407.06
107	Avail_Thrust_M3	Coefficient for third order mach term in thrust determination	0	-27683.1
108	Avail_Thrust_A1	Coefficient for first order angle of attack term in thrust determination	0	2.346588
109	Drag_Coeff_Con	Constant value for drag determination	0.0052623	0.0040243
110	Drag_Coeff_M1	Coefficient for first order mach term in drag determination	-0.097529	-0.292672
111	Drag_Coeff_M2	Coefficient for second order mach term in drag determination	0.0721954	0.5913677
112	Drag_Coeff_M3	Coefficient for third order mach term in drag determination	0	-0.240227
113	Drag_Coeff_A1	Coefficient for first order angle of attack term in drag determination	0.0043428	-0.007449
114	Drag_Coeff_A2	Coefficient for second order angle of attack term in drag determination	-0.001068	0.0025667
115	Drag_Coeff_A3	Coefficient for third order angle of attack term in drag determination	0	0.000035
116	Drag_Coeff_MA1	Coefficient for first order mach times angle of attack term in drag determination	-0.013219	0.0017992
117	MinG	Minimum G for target normal acceleration	1.2	1.2
118	Roughness_Factor	Weighting of terrain roughness in determination of MSL altitude for trajectories	-0.4	-0.4
119	Width_of_T_divisor	Divisor for determining "T" intersection of	8	8

Table A-1 (Continued)
F/A-18 TAWS Configurable Parameters

Array OffSet	Parameter Name	Description	F-18CD value	F-18EF value
		VRT		
120	High_Altitude_G_Bucket_Delta	Reduction in G-limiter value due to transonic flight at high altitudes	1.0	1.0
121	Low_Altitude_G_Bucket_Delta	Reduction in G-limiter value due to transonic flight at low altitudes	1.0	1.7
122	G_Bucket_Altitude_Threshold	Altitude at which the high/low altitude G-bucket delta changes	0	15000
123	G_Bucket_Minimum_Mach_NoStores	Minimum mach number at which the G-bucket can be engaged with STORES flag not set	0.95	0.941
124	G_Bucket_Minimum_Mach__Stores	Minimum mach number at which the G-bucket can be engaged with STORES set	0.91	0.905
125	G_Bucket_Maximum_Mach	Maximum mach number at which the G-bucket can be engaged	1.04	1.045
126	Corner_Speed	Minimum airspeed required to produce the maximum G	xxx[1]	xxx[1]
127	Maximum_Bank_Angle	Maximum bank angle for which this reduction in pilot response time applies	30	30
128	Minimum_Airspeed	Minimum airspeed for which this reduction in pilot response time applies	400	400
129	Maximum_Airspeed	Maximum airspeed for which this reduction in pilot response time applies	525	525
130	Reduced_Pilot_Delay	Reduced pilot response time for nuisance prevention	1.3	1.3
131	Minimum_Dive_Angle	Minimum dive angle for which this reduction in pilot response time applies	5	5
132	Maximum_Dive_Angle	Maximum dive angle for which this reduction pilot response time applies	25	25

Note 1: Actual number omitted due to security classification.

Table A-2
F/A-18 TAWS Sensor Hierarchy and Effect

System Mode	Terrain Definition Mode	Attitude and Acceleration	Position Source	Velocity Source	MSL Altitude[2]	DTED	RADALT
OPERATE	DTED	INS	Aided INS, GPS[1]	Aided INS, GPS, INS[1]	GPS, INS BARO, ADC BARO	Good	Good or Bad
OPERATE	FLAT EARTH	INS	INS	Aided INS, GPS, INS	GPS, INS BARO, ADC BARO	Good	Good
OPERATE	FLAT EARTH	INS	Aided INS, GPS	Aided INS, GPS, INS	GPS, INS BARO, ADC BARO	Bad	Good
OPERATE or COAST[3]	FLAT EARTH	INS	Aided INS, GPS, INS	Aided INS, GPS, INS	GPS, INS BARO, ADC BARO	Bad	Bad
BYPASS	N/A	NONE	Aided INS, GPS, INS	Aided INS, GPS, INS	GPS, INS BARO, ADC BARO	Good or bad	Good or Bad
BYPASS	N/A	INS	Aided INS, GPS, INS	NONE	GPS, INS BARO, ADC BARO	Good or bad	Good or Bad

Notes:
[1] The first priority used for position is the Aided INS mode, where GPS position is used to update the INS regularly. Falling back to solely GPS-only degrades performance slightly, and has no effect on System Mode. The same logic prevails for velocities.

[2] The MSL altitude is set with the following priority (highest to lowest): GPS; INS BARO; ADC BARO. Differences in MSL altitude source have no effect on System Mode.

[3] The TAWS can go to the COAST mode only when the terrain has been determined to be level and the TAWS is in the FLAT EARTH mode.

APPENDIX B

Table B-1
F/A-18 TAWS Developmental Test Plan Test Hazard Analysis

HAZARDOUS CONDITION	CAUSE	EFFECT	RISK ASSESSMENT	PRECAUTIONARY MEASURE	HAZARD LEVEL
Controlled Flight Into Terrain (CFIT) during Nuisance Cue Testing	Loss of situational awareness in close proximity to terrain.	Loss of aircraft/aircrew.	Low risk given proper aircrew experience/practice, test briefing, and execution.	– Required weather: day VMC with defined horizon and visual contact with terrain. – All maneuvers are operationally representative; no special maneuvers are required nor desired. Pilot's focus will be on flying the maneuver; any nuisance warnings will be automatically recorded on instrumentation. Any pilot comments or observations will be recorded verbally following aircraft recovery and between maneuvers. – Provide sufficient proficiency through simulators and/or warm-up flights. **Low Level Navigation** – Chase aircraft required on 200 ft low levels (Chase min altitude 500 ft). – Pilot must fly 500 ft low level build up prior to 200 ft – Both 500 ft and 200 ft low level will be flown over the same route. – Back seat safety aircrew required. **Weapons** – Standard weapons dive delivery profiles in accordance with the TACMAN, reference 7. – Practice weapons dive delivery profiles will be flown initially 1000 ft above the lowest test point altitude. – Recoveries at the stepped up altitude will be monitored to verify the actual altitude lost during recovery does not exceed predicted altitude loss. – Flight parameters are monitored real-time by a safety monitor and call for recovery if safety parameters are exceeded. – Radar altimeter set at minimum release/initiate recovery altitudes. Warning bug checked prior to maneuvers. – G warm-up maneuvers. – Back seat safety pilot required.	I/D CAT B

Table B-1 (Continued)
F/A-18 TAWS Developmental Test Plan Test Hazard Analysis

HAZARDOUS CONDITION	CAUSE	EFFECT	RISK ASSESSMENT	PRECAUTIONARY MEASURE	HAZARD LEVEL
Controlled Flight Into Terrain during LAT flights	Reduced roll performance in INT loading	Loss of aircraft/aircrew.	Low risk given proper aircrew experience/practice, test briefing, and execution.	**LAT** – Thorough LAT brief conducted prior to flight. – LAT dive rules reviewed prior to each maneuver. – Back seat LAT instructor safety pilot required. – Prerequisite 500 ft low level. – Ground monitoring of critical flight parameters. – LAT flown to comfort level, but no lower than 200 ft. – LAT pre-flown in simulator at flight test conditions and weights.	

Table B-1 (Continued)
F/A-18 TAWS Developmental Test Plan Test Hazard Analysis

HAZARDOUS CONDITION	CAUSE	EFFECT	RISK ASSESSMENT	PRECAUTIONARY MEASURE	HAZARD LEVEL
Controlled Flight Into Terrain (CFIT) during CFIT Protection (Simulated loss of SA)/ Functional Testing.	Loss of situational awareness, misapplied recovery controls, reliance on TAWS warnings.	Loss of aircraft/aircrew.	Low risk given proper aircrew experience/practice, test briefing, and execution.	– Functional tests will be completed prior to simulated loss of SA tests. – G warm up, recoveries targeting g onset rat es, sustained g and roll rates required for TAWS recoveries will be practiced through warm up events. – Use of safety buffers to raise TAWS warning altitudes. – Recoveries will be practiced at the fastest and slowest test speeds in configuration CR prior to CR tests and at the slowest test speed in configuration PA prior to PA tests. – Provide sufficient proficiency through simulator sessions. – Back seat safety pilot required for CFIT protection testing. – Radar altimeter hard-bug and BARO soft -bug set at terminate run altitude and warning bugs checked prior to maneuvers. – Flight parameters are monitored real-time by a safety monitor and call for recovery if safety parameters are exceeded. – Weather day VMC with defined horizon and visual contact with terrain. – Brief knock-it-off parameters prior to maneuver entry. – Reviewed GPWS AV-8B mishap report OPNAV 3752-1 and applied lessons learned to test procedures.	I/D CFIT Protection CAT B Functional Tests CAT A
G Induced Loss of Consciousness (GLOC) during CFIT Protection (Simulated loss of SA/ Functional Testing).	High G-onset rates during a recovery maneuver.	Loss of consciousness possibly leading to loss of aircraft/aircrew.	Low risk given extensive aircrew experience and warm-up.	A G warm-up will be performed prior to t esting (IAW NSATS/NWTC SOP, reference 8). Aircraft recoveries will be practiced in the simulator prior to test flights and during practice maneuver prior to test events. Safety pilot starts G straining maneuver prior to expected TAWS warning altitude.	I/D CFIT Protection CAT B Functional Tests CAT A

Table B-1 (Continued)
F/A-18 TAWS Developmental Test Plan Test Hazard Analysis

HAZARDOUS CONDITION	CAUSE	EFFECT	RISK ASSESSMENT	PRECAUTIONARY MEASURE	HAZARD LEVEL
Aircraft overstress.	Overly aggressive dive recovery. Excessive rate of descent on landings.	Down aircraft, inspection requirement.	Low risk given proper aircrew experience/practice, test briefing, and execution.	G warm up, recoveries targeting G-onset rates, sustained G, and roll rates required for TAWS recoveries will be practiced through warm up events. Ground monitoring of critical flight parameters. LSO monitor landing parameters during off nominal approaches. Brief maximum landing weights. RTB if overstress occurs and analyze to determine cause before proceeding with test.	III/D CAT A
Bird-strike.	Operating at altitudes where birds normally fly.	Possible damage to or loss of aircraft. Possible injury to or loss of aircrew.	Potential risk based on frequent low level operations during T&E.	Visual look-out by aircrew will be maintained at all times. If bird-strike should occur, aircraft will climb above 10KFT MSL, conduct a controllability check, and return to base or a suitable divert. Chase aircraft on 200 ft low level routes.	III/C CAT B

VITA

Gregory Glen was born in 1965 in Ridgecrest, CA.. He graduated from Sherman E. Burroughs High School in 1983. In 1991 he was awarded a Bachelor of Science Degree in Electronics Engineering from California State University, Chico. He graduated from the United States Navy Test Pilot School in December of 1998 and is currently employed by the Naval Air Warfare Center, Weapons Division at China Lake California working on the F/A-18 Program.