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Lessons learned from the developmental flight testing of the Terrain Awareness Warning System

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To the Graduate Council:

I am submitting herewith a thesis written by Randolph J. Bresnik entitled "Lessons learned from the developmental flight testing of the Terrain Awareness Warning System." 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.

R. Richards, Major Professor

We have read this thesis and recommend its acceptance:

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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LESSONS LEARNED FROM THE DEVELOPMENTAL FLIGHT TESTING OF THE TERRAIN AWARENESS WARNING SYSTEM

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

Randolph J. Bresnik
December 2002

DEDICATION

This thesis is dedicated to Major Mike “Kuddy” Kudsin, USMC, Major Mike “Woody” Curry, USMC, and countless other aviators who perished doing what they loved, flying, but who never knew the mortal danger awaiting them.

ACKNOWLEDGMENTS

The patience of the TAWS test team was pivotal to the completion of the flight test of TAWS as well as the completion of this thesis. Special thanks go out to C.W. Shafer, Tom Anderson, Tom Hanrahan, Michael Johnson, James Cotugno, and Norm Eliasen. Also, I would especially like to thank Dr. R. Richards for his patience, guidance, and advice throughout my Test Pilot and Graduate education as well as the pursuit of this thesis.

ABSTRACT

The Ground Proximity Warning System (GPWS) currently fielded on the F/A-18A/B/C/D/E/F and AV-8B aircraft is a great safety-backup system that alerts the pilot of an impending Controlled Flight Into Terrain (CFIT) condition. However, it does have one major limitation: the reliance on the look-down radar altimeter, which results in little or no CFIT protection in rising terrain.

The Terrain Awareness Warning System (TAWS) is the generational evolution of GPWS that provides the predictive, or look-ahead, capability sorely missing from the current system. Utilizing aircraft positioning from the Global Positioning System (GPS) and an onboard Digital Terrain Elevation Data (DTED), TAWS computes recovery trajectories and presents a combination of aural and visual warnings when necessary to cue the pilot to avoid a CFIT condition. TAWS, without being solely reliant on the radar altimeter, has the ability to calculate and present appropriate warnings regardless of aircraft position or attitude. Ultimately, TAWS has to walk a fine line between providing timely warnings that allow the pilot to conduct maximum performance maneuvering during all mission roles, without the impedance of nuisance cues. At the heart of TAWS is a generic algorithm that can be tailored to specific aircraft performance and mission characteristics.

This thesis examines all aspects of the flight test of TAWS: the history of GPWS and TAWS in aviation, the conundrum of how to plan a flight test of a terrain avoidance system in close proximity to the ground without endangering aircrew or aircraft, the use of simulation, additional safety precautions, results, lessons learned for program managers and test pilots, and future applications.

PREFACE

The analyses, opinions, conclusions and recommendations expressed herein are those of the author and do no represent the official position of the Naval Air Warfare Center, the Naval Air Systems Command, or the Department of the Navy. Data presented in this thesis were obtained from a Department of the Navy test program and not from dedicated flight test to support this thesis project. The author's recommendation should not be considered attributable to any of the aforementioned authorities or for any purpose other than fulfillment of the thesis requirements.

The author was the project officer for TAWS. Of the many test sorties of TAWS he flew, he also executed the first flight and the last test flight of TAWS in the F/A-18 developmental test program.

The Terrain Awareness Warning System (TAWS) discussed in this thesis has been tested only in the F/A-18 Hornet and Super Hornet thus far. The Hornet and Super Hornet are highly maneuverable, tactical military aircraft; therefore, military TAWS excludes comparison to the system of the same name in civilian aircraft.

A patent was granted in August of 2002 for the TAWS algorithm. Therefore, any discussion of the TAWS algorithm will be limited by the proprietary nature of the patent.

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LIST OF ABBREVIATIONS AND TERMINOLOGY

ACI	Amplifier Control, Intercommunication
AGL	Above Ground Level
CFIT	Controlled Flight Into Terrain
COTS	Commercial Off-The-Shelf
deg	Degree
DMC	Digital Map Computer
DTED	Digital Terrain Elevation Database
EGPWS	Enhanced Ground Proximity Warning System
FAA	Federal Aviation Administration
ft	Feet
FY	Fiscal Year
GCAS	Ground Collision Avoidance System
GPS	Global Positioning System
GPWS	Ground Proximity Warning System
HUD	Heads-Up Display
ICAO	International Civil Aviation Organization
JHMCS	Joint Helmet Mounted Cueing System
lbs	Pounds
m	Meter
MC	Mission Computer
NAPIE	Navigation Avionics Platform Integration Emulator
NAS	Naval Air Station
NAFOD	No Apparent Fear Of Death
NIMA	National Imagery and Mapping Agency
OFP	Operational Flight Program
ORT	Oblique Recovery Trajectory
ORD	Operational Requirements Document
PCMCIA	Personal Computer Memory Card International Association
PRT	Pilot Response Time
PVI	Pilot-to-Vehicle Interface
SRTM	Shuttle Radar Topography Mission
STS	Shuttle Transport System
TAMMAC	Tactical Aircraft Moving MAp Capability
TAMPS	Tactical Aircraft Mission Planning System
TAWS	Terrain Awareness Warning System
VRT	Vertical Recovery Trajectory
V&V	Verification and Validation

AIRCRAFT DESIGNATIONS

All U.S. military aircraft are designated with a letter denoting the mission type followed by a number of that model aircraft. Subsequent letters to the model number indicate the model variant. In the course of this thesis, F/A-18 is commonly used. The F/A indicates the mission type of Fighter / Attack. The 18 denotes the model commonly known as the “Hornet”. The model variant of “D” indicates the fourth version of the Hornet, a two-seat aircraft. The model variant of “F” indicates the sixth version known as the “Super Hornet”, also a two-seat aircraft.

CHAPTER 1

INTRODUCTION

THE NEED FOR A CFIT SOLUTION

> “A controlled flight into terrain (CFIT) accident is defined as a collision in which an aircraft, under the control of the crew, is flown into the terrain (or water) with no prior awareness on the part of the crew of the impending disaster.”[1]

> “CFIT accidents are the most severe aircraft accidents. These kinds of accidents occur when an otherwise airworthy airplane is inadvertently flown into the ground or water. The number of fatalities per accident is extremely high as compared to any other type of accident. They also generally result in complete destruction of the airplane.”[2]

Both of these very stark descriptions of controlled flight into terrain were penned by the same author, albeit 16 years apart. Simply stated: throughout aviation history, controlled flight into terrain (CFIT) has always been one of the leading causes of the loss of aircrew and aircraft. Since 1931 more than 40,000 passengers and crew have lost their lives in terrain collision accidents worldwide.[3] Still today, CFIT accidents rank as the number one cause of aviation fatalities worldwide with 60% of fatalities over the last ten years attributed to CFIT accidents.[4] The ultimate toll in terms of both man and machine is always extracted in a CFIT accident as the ground always wins the contest. With these appalling statistics it was clearly evident that something had to be done to help keep pilots from flying a perfectly airworthy aircraft into the ground. In an effort to arm the pilot with the necessary cueing to combat CFIT, various Ground

Proximity Warning Systems (GPWS) and Ground Collision Avoidance Systems (GCAS) have been developed and tested by the military in the last twenty-five years. The Terrain Awareness Warning System (TAWS) is the generational evolution of GPWS.

A BRIEF HISTORY OF GPWS AND TAWS

GPWS is a simple system. As its name implies, Ground ***Proximity*** Warning only alerts the pilot to closeness with the terrain. When it was first conceived, technology limited the options for designers. All GPWS to date are limited by their sole reliance on the radar altimeter. Radar altimeters are instruments mounted on the underside of the aircraft that provide measuring of true height above the exact terrain at that exact moment in flight. For aircraft that aren't moving or terrain that isn't changing (flat or water), a radar altimeter based system can provide acceptable CFIT protection. Unfortunately, some aircraft are highly maneuverable frequently flying outside the operating envelope of the radar altimeter in terms of high bank and pitch angles. When the terrain is not flat, reliance on the radar altimeter precludes any forward or "look-ahead" capability. This is due to the radar altimeter staring straight down therefore being unable to predict rising terrain in the aircraft's flight path resulting in little or no protection.

TAWS is a generational evolution of the GPWS providing protection that is not limited by only a look-down capability. TAWS was previously known as the Enhanced Ground Proximity Warning System (EGPWS). TAWS is 'enhanced' because it uses a terrain database to compare to Global Positioning System (GPS) inputs. This ability to know where the aircraft is, where the aircraft will be, and the height of the terrain all around the aircraft allows TAWS to alert the pilot of terrain that could be in the aircraft's flight path. This is the "look-ahead" capability missing from the earlier GPWS.

The requirement for the installation of GPWS in all domestic airliners was mandated following the 1974 TWA crash at Washington Dulles International Airport.[5] As a result of this initial implementation of GPWS, there was an immediate order-of-magnitude reductions in CFIT mishaps of commercial air carriers.[6] In 1978 the Federal Aviation Administration (FAA) broadened the mandate for GPWS to include smaller jet aircraft with 10 or more passenger seats.[7] Initially turboprop aircraft were excluded from the mandate because it was thought that their slower speeds made them less likely to have a CFIT accident. Time has shown, however, that it is not the type of aircraft that is the root cause of these CFIT accidents but rather the aircrew who have lost situational awareness. In 1992 the FAA correctly expanded the GPWS mandate to turboprops with 10 or more passenger seats.[7] With the subsequent improvements in technology both in and out of the cockpit, the latest mandate effective March 2001 required the installation of TAWS in all U.S. registered turbine-powered aircraft with 6 or more passenger seats. Therefore, new aircraft rolling off the assembly line after

29 March 02 must immediately meet TAWS requirements while aircraft manufactured before that date must augment or replace existing GPWS systems by 29 March 2005.[8]

The effort to reduce CFIT accidents is truly global, not just a domestic U.S. concern. The International Civil Aviation Organization (ICAO) works with the U.S. FAA to ensure compliance by regional civil aviation authorities. The international community is working to meet the 1 January 2003 deadline for installation of TAWS in all aircraft with 30 or more passenger seats and a maximum takeoff gross weight of greater than 33,067 lbs.[9] Many foreign aircraft manufacturers have also developed GPWS and TAWS-like systems for many of their military aircraft.

THE MILITARY APPLICATION OF GPWS AND TAWS

Military aircraft operate in much more varied conditions and larger flight envelopes than do civil aircraft. Therefore, military system operating requirements for GPWS or TAWS are much more robust than those for civil aircraft. Military aircrew need directive warnings to recover the aircraft from an impending CFIT condition without hindering their ability to fly aggressive combat and combat-support missions.

The Department of the Navy effort to reduce CFIT accidents was initiated with the 1987 Operational Requirements Document for GPWS (GPWS ORD).[6]

GPWS has been in operational fleet aircraft, namely the F/A-18 and AV-8B, for the last 6 years. It is important to note, however, that GPWS is not a performance aid to change the way a pilot would maneuver the aircraft. GPWS is a safety backup system only, which assesses the aircraft's current state and alerts the pilot of an impending CFIT condition. Early GPWS versions had far too many flight regimes where nuisance cues were common. Nuisance cues are those warnings that the aircrew believed were invalid or did not require immediate aircrew response. Nuisance cues eroded pilot confidence and led to a general pilot procedure of disabling the system prior to takeoff. While it could be considered better to have extra warnings rather than not enough, consider operations in a hostile environment. If the aircrew were conducting low-level flight and received a GPWS warning that was false, they may automatically respond to a "pull-up" warning abandoning their terrain masking attempts thereby entering a threat weapon system envelope putting the aircraft at greater risk. If the warning were genuine, then the aircrew would have to avoid the terrain as a first priority and then deal with the threat weapon system. Since initial GPWS implementation, CFIT has accounted for 29% of all F/A-18 losses.[10] Two subsequently fielded versions of GPWS targeted enhancing CFIT protection, while at the same time eliminating nuisance cues. Feedback from the fleet indicates that pilot confidence in GPWS has improved and maintenance records indicate GPWS usage is now normal practice. However, CFIT still ranks third overall behind out-of-control flight and engine malfunctions for all of Naval Aviation aircraft losses.[10]

Enter TAWS, the Navy and Marine Corps first predictive ground proximity warning system for tactical aircraft. As aircraft and weapon systems became more complex and mission scenarios became increasingly demanding, it became clear that the look-down capability of GPWS was providing insufficient CFIT protection. This taken with the inherent limitations of GPWS discussed previously, drove the Department of the Navy to the capabilities a system like TAWS could provide. As stated previously, TAWS implementation in the civil aviation industry is not as robust as that required for military missions. Civil adaptations of TAWS do not function at the speeds or incorporate aircraft specific parameters that the military version does. The remainder of this thesis will address the military implementation of TAWS. Highly complex, TAWS must interface with not only the radar altimeter, but also the inertial navigation system, global positioning system, air data computer, aircraft mission computer, and digital terrain elevation database (DTED). This interfacing allows for increased CFIT protection throughout the entire flight regime, flight over wide variations in terrain (figure 1) during maneuvers that exceed sensor limits, and during takeoff and landing, all without increasing the already heavy pilot workload.

PURSUIT OF A SOLUTION FOR CFIT

There are two major philosophical paths that can be taken when pursuing a solution for CFIT. One philosophy is to develop a system that will save *everyone* in a CFIT condition. This approach is especially applicable to commercial and

Figure 1
F/A-18A'S OVER THE GRAND CANYON
Photograph by the Author

military–transport aircraft where operations are in well-defined envelopes that are rarely exceeded. These flight envelopes are well defined because larger aircraft are not highly maneuverable and can be expected to be flown along very predictable flight trajectories in the execution of all their missions. The second philosophy is to *avoid nuisance warnings* at all costs. This will result in a system that will save *most*, but not necessarily all, aircraft in a CFIT condition. The U.S. Navy and Marine Corps developed GPWS and then TAWS for tactical aircraft with the guiding philosophy of *avoiding nuisance warnings*.

Once a design philosophy has been determined, two approaches to integration with the aircrew and aircraft are available: active or passive. The latest U.S. Air Force Ground Collision Avoidance System (GCAS) tested an automatic recovery maneuver (active) through the *aircraft* flight control system if the pilot has not taken corrective action by the time a CFIT condition is determined.[11] The U.S. Air Force has been guided by the "save everyone" approach. Navy and Marine Corps development of GPWS and then TAWS, has been guided by the selection of the "save most" approach, maintaining the requirement to have no nuisance warnings presented to the pilot. This resulted in the *passive* integration with the aircraft (no automatic recovery), but an *active* set of cues to alert the pilot to recover.

Nuisance cues or "crying wolf" previously lead to a lack of confidence in the system and delays in pilot response to "real" warnings. GPWS and TAWS provide warnings only 3 to7 seconds prior to ground impact. Depending on flight conditions, this is not sufficient time for the pilot to determine whether a warning is real or not and take corrective action. By relying solely on pilot cueing (passive), pilots must understand that they are in an emergency situation, believe the cues presented to them are real and respond with minimal reaction time. However, in the pursuit to eliminate nuisance cues there lies the risk of inadvertently reducing CFIT protection. In the end, the goal of the TAWS approach is to allow the pilot to continue flying in all flight regimes they do now without changing any tactics or training following the incorporation of this system.

CHAPTER 2

WHAT IS TAWS?

TAWS DESCRIPTION

The sole purpose of GPWS and TAWS is to warn the pilot that ground impact is imminent and provide an indication of what corrective action should be taken via visual and aural cues. GPWS is an algorithm integrated into the aircraft mission computer software configuration set. GPWS inputs and operation are depicted in figure 2.

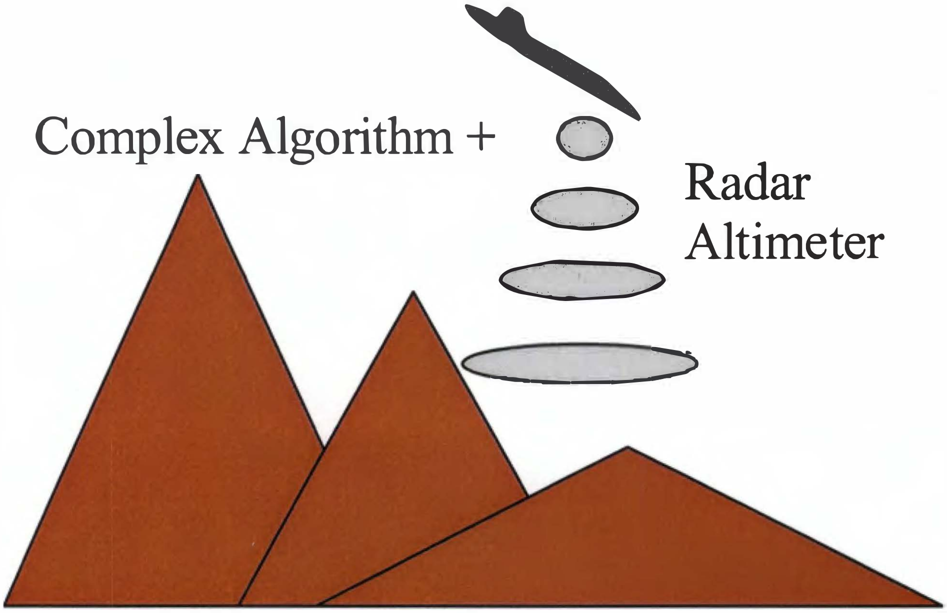

Figure 2
GPWS INPUTS AND OPERATION

In comparison, TAWS is an algorithm integrated in the Digital Map Computer (DMC) of the Tactical Aircraft Moving MAp Capability (TAMMAC) system. The TAMMAC system provides the latest generation of digital moving map cockpit presentation that is combined with a new capability to view previously stored imagery. Digital Terrain Elevation Data (DTED), or the digital portion of the map containing elevation data, is co-located with the TAWS algorithm in the DMC. TAWS inputs, operation, and recovery trajectories are depicted in figure 3.

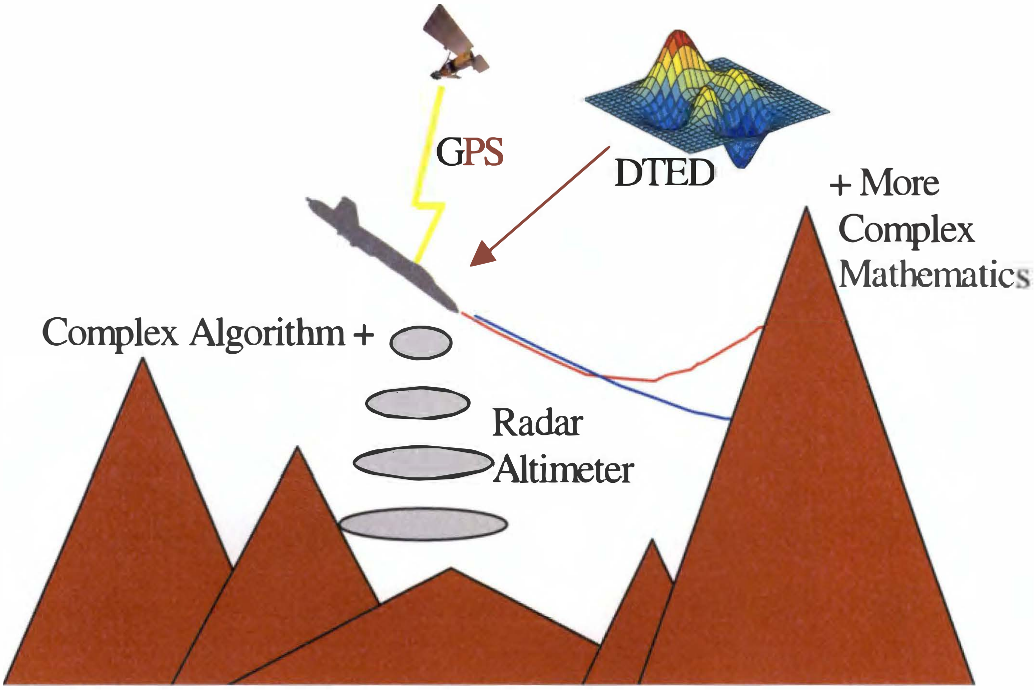

Figure 3
TAWS INPUTS, OPERATION, AND RECOVERY TRAJECTORIES

TAWS compares the DTED to the aircraft position obtained from GPS and INS to predict potential ground impact. This allows TAWS to provide the forward, or look-ahead capability, not possible with a radar altimeter reliant system such as GPWS. The predicted recovery profile, described in the next section, is presented to the pilot who then executes the escape maneuver.

Areas of CFIT protection are based on aircraft mission, aircraft type and installed systems available to implement TAWS. Areas of CFIT protection by TAWS include: excessive rate of descent, excessive closure with terrain, negative climb rate or altitude loss after takeoff, flight into terrain when not in a landing configuration, excessive bank angle, and excessive descent below glideslope on an instrument approach.[6]

There are several basic fundamentals and assumptions in the design and function of TAWS. First, TAWS queries the DTED up to 340 times per second requiring the TAWS algorithm to reside in the same location (TAMMAC DMC) as the DTED. Second, TAWS predicts the pilot will require 1.3 seconds to acknowledge the warning and initiate a recovery. Third, the TAWS minimum terrain clearance altitude is set at 50 ft Above Ground Level (AGL) for aircraft in the cruise configuration (gear: up, flaps: automatic). Fourth, the predicted recovery assumes the aircraft will be rolled to wings-level (if so required), and loaded to a load factor of 5 (or 80% of available load factor when below best maneuvering airspeed). Fifth, TAWS assumes the throttles will be retarded to IDLE when above best maneuvering airspeed and set to maximum afterburner when below. This allows for an accurate prediction of the acceleration during the recovery and the potential change in available load factor.

Operationally, as aircraft location is determined and altitude is adjusted for sensor and DTED errors, TAWS utilizes this fused sensor data to continuously compute two recovery trajectories, *vertical* and *oblique.*[10] The vertical recovery trajectory (VRT) assumes the aircraft will be rolled to wings-level followed by a longitudinal pull to a load factor of 5 (or 80% of available). The oblique recovery trajectory (ORT) assumes the current bank angle will be maintained and an increase in load factor to 5 (or 80% of available) in the turn will follow. The recovery trajectories are broken down to five components that make up the recovery. The components are: the pilot response delay, roll response delay, load factor-delay phase, load factor-onset phase, and dive recovery phase. The vertical and oblique recovery trajectories are depicted in figure 4. As long as one of the constantly computed trajectories does not intercept the DTED, no warning is issued because there is still a way out of the potential CFIT. If both recovery trajectories intersect the terrain database, then a pilot warning is presented. The use of two recovery trajectories greatly reduces the probability of nuisance warnings.

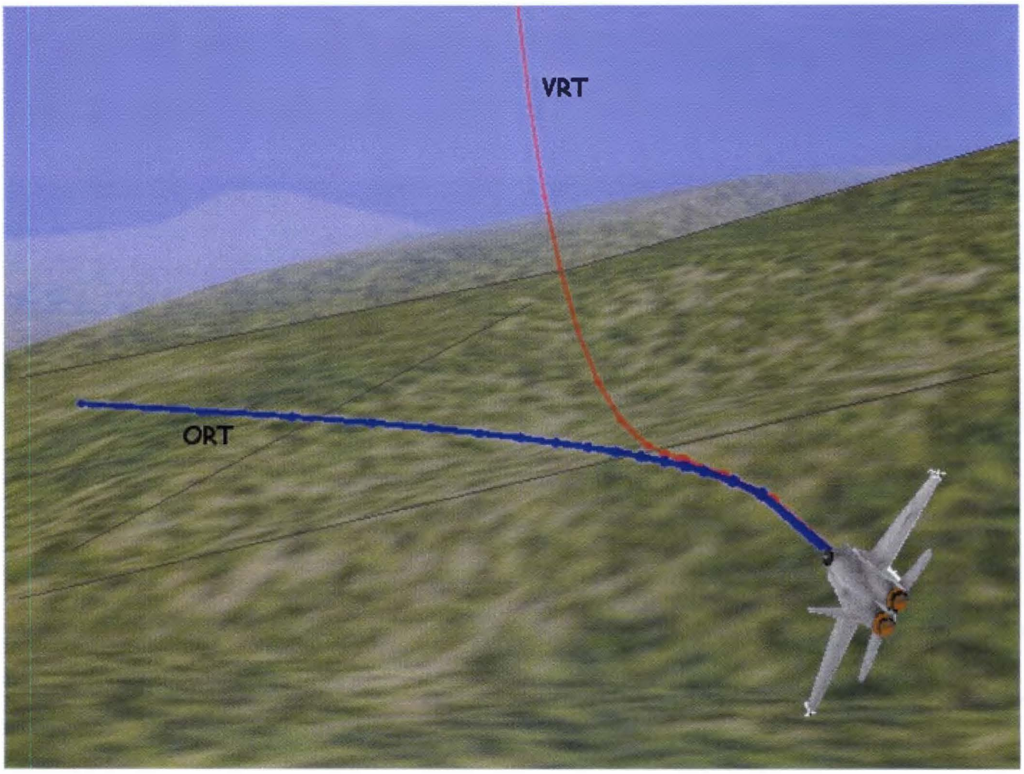

Figure 4
TAWS VERTICAL AND OBLIQUE RECOVERY TRAJECTORIES
Figure Courtesy of T.E. Anderson

Standard commercial off-the-shelf (COTS) Personal Computer Memory Card International Association (PCMCIA) cards are used for interface between pre-flight mission planning and the DMC in the aircraft. The uses of industry standard computer cards enhance TAWS in several ways. First, cost is greatly reduced due to increased availability. Second, as data storage continues to increase over time, cards with more capability can be utilized in the existing hardware resident in the aircraft. During pre-mission planning, data is written to the cards via the Tactical Aircraft Mission Planning System (TAMPS). Additionally, these cards are loaded with a configurable parameter file used to configure TAWS for that particular aircraft model. The configurable parameters file tells TAWS in what aircraft it is hosted and loads the numerous aircraft specific characteristics and performance parameters, this enables TAWS to present appropriate and timely warnings for the given platform. Consequently, the configurable parameters feature is what enables a single TAWS software build to support numerous aircraft platforms.

TAWS is fully automatic operating ‘behind the scene’ requiring no pilot input. If TAWS were to cease operation, GPWS is still functioning in the background within the aircraft mission computer and would provide the same "look-down" protection afforded prior to TAWS integration. The most versatile feature of TAWS is that at its heart, it is a software algorithm of generic design that can be tailored to fit any aircraft with a TAMMAC-like DTED system.

TAWS COCKPIT CUEING

TAWS warnings are presented to the pilot through directive voice commands and an arrow in the Head Up Display (HUD), figures 5 and 6. The HUD arrow always points in the direction of aircraft recovery and is issued simultaneously with the voice command.

The voice commands or aural warnings are the primary means of alerting the pilot to the impending CFIT condition. They act as a wake up call to the pilot who has lost situational awareness. The directive nature of the cues is designed to require little thought thus minimizing the pilot response delay. Aural warnings consist of five urgent commands to direct the pilot's initial response. "PULL-UP….PULL-UP!" is issued if bank angle is less than 45 degrees or the oblique recovery is the preferred exit path. "ROLL-RIGHT…ROLL-RIGHT!" or "ROLL-LEFT…ROLL-LEFT!" is issued if the bank angle is greater than 45 deg. "POWER…POWER!" is issued if bank angle is less than 45 deg, airspeed is less than 200 kts and above the angle of attack threshold. "CHECK GEAR!" is issued if the aircraft descends below 150 ft AGL as if for landing without the landing gear extended. The voice messages may be given in combination. The most common combination would be a "ROLL-RIGHT or LEFT!" followed by a 'PULL-UP!" voice message. The combination of the directive aural warning and HUD arrow is designed to provide the pilot with unambiguous information

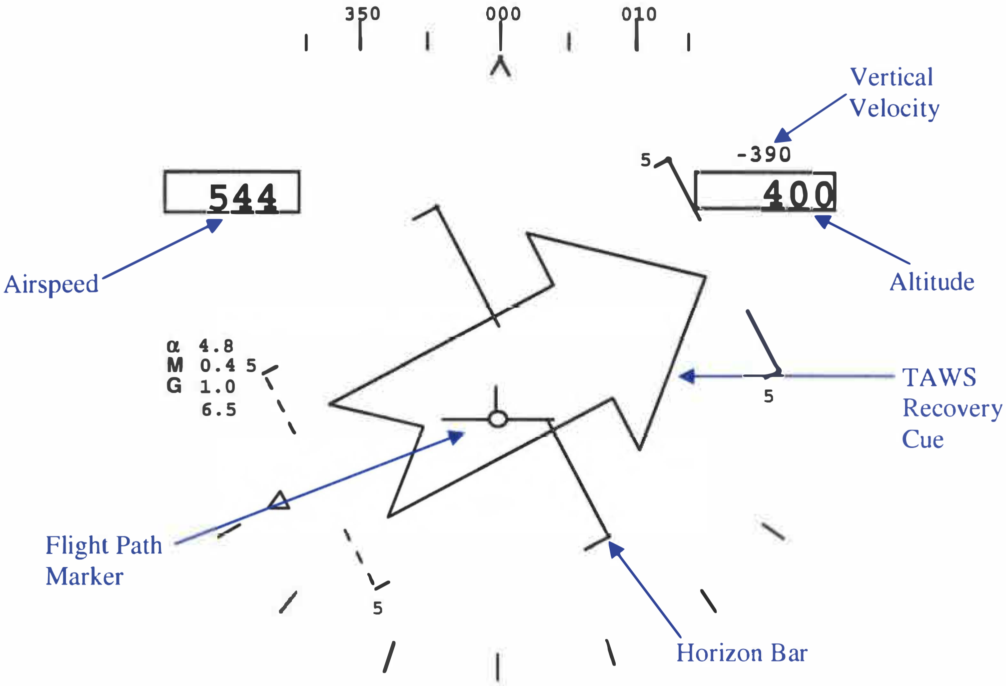

Figure 5
HUD CUE FOR VERTICAL RECOVERY TRAJECTORY WARNING

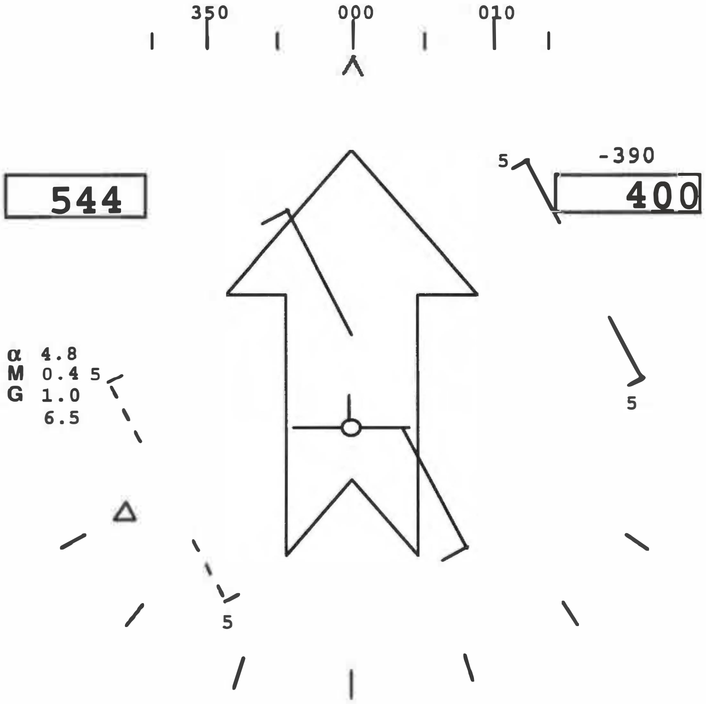

Figure 6
HUD CUE FOR OBLIQUE RECOVERY TRAJECTORY WARNING

that allows for timely and appropriate responses to the warnings to avoid ground collision. Since TAWS warnings are intended to be heard infrequently and only in dire circumstances, it was an absolute requirement that there be no ambiguity in the words or voice inflection used.

CHAPTER 3

TAWS PROGRAMATICS

TAWS utilizes a collection of existing and developing systems within the Hornet and Super Hornet. The Tactical Aircraft Moving MAp Capability (TAMMAC) provides the Digital Map Computer (DMC) in which the Digital Terrain Elevation Database (DTED) is stored. The Tactical Aircraft Mission Planning System (TAMPS) generates and loads DTED in the on-board aircraft TAMMAC system via standard PCMCIA cards. The Joint Helmet Mounted Cueing System (JHMCS) is a system unrelated to the *operation* of TAWS. The TAMMAC replaces existing avionics hardware in the avionics bay. Because TAMMAC is compact, it creates enough space for the avionics hardware of the JHMCS. Thus, in order to install the JHMCS within the F/A-18 C/D Hornet, acquisition of TAMMAC is required. TAMMAC was deployed operationally for the first time on the F/A-18 E/F Super Hornet in the summer of 2002, with TAWS slated for second deployment on the Super Hornet in FY 03. TAMMAC, and hence TAWS, are not slated to be acquired for the F/A-18 C/D Hornet until FY 05.

CHAPTER 4

PREPARING FOR TAWS FLIGHT TEST

TEST PLANNING

Tactically realistic testing of a CFIT protection system, that is an emergency system providing a last-ditch warning, requires significant planning. When flying an agile, tactical aircraft against actual terrain, if the system does not operate properly, the aircraft will likely be beyond the point of safe terrain clearance. Obviously, this is an unacceptable risk in flight test. The conundrum then lies in how to safely and adequately test a CFIT protection system without creating a mishap. Testing at altitude is desirable for risk reduction but it has some less desirable consequences that must be considered, such as: reduced aircraft performance, less accurate data, and absence of visual ground rush cues to the pilot. Aircraft turn and engine performance at altitude is obviously much less than just above the ground. If the testing were conducted at altitude, then the data obtained would result in recovery cues presented to the pilot sooner than required when at lower altitudes. This is the definition of a nuisance cue. Perhaps more importantly, in testing at altitude, the pilot's perception of a nuisance warning degrades due to the absence of visual ground rush cues. This may ultimately result in reduced protection because the algorithm may have been tailored to eliminate “perceived” nuisances that would not have been nuisances had the testing been done in close proximity to the ground. Therefore, the ideal environment to test TAWS would be as close to the ground as safely possible. Fortunately, there have been many years of experience testing GPWS that provided an excellent foundation for TAWS testing. The combination of minimal buffer altitudes, simulation, and re-stimulation of flight data in the simulator proved to be the recipe for robust yet streamlined testing while limiting risk to aircrew and aircraft.

Two categories of testing were required for TAWS: nuisance cue and CFIT protection testing. Nuisance cue testing was the easiest to plan as operationally representative maneuvers were performed with no additional safety requirements or concerns. Normal everyday flying and tactics could be flown with existing training to see if there were any nuisance cues. CFIT protection was much more difficult to plan as extreme flight regimes and aircraft attitudes were required to be tested. Flight test required on-board high-speed data recording as well as real-time monitoring and recording of flight test and safety parameters. Throughout TAWS testing, an overall build-down test approach was utilized for altitudes and build-up for airspeeds and dive angles.

TEST SCHEDULE

Developmental flight test of TAWS consisted of three planned flight phases. The first two flight test phases were Developmental testing on the F/A-18C/D and F/A-18E/F respectively. The third phase was Verification and Validation (V&V) of the final TAWS software build common to both the F/A-18C/D and E/F. Planned flight test location and dates were: Phase 1- F/A-18D, Naval Air Station (NAS) Patuxent River, July-August 2000, Phase 2 - F/A-18F, NAS China Lake, November-December 2001, Phase 3 – F/A-18D and F/A-18F, NAS Patuxent River and NAS China Lake, April-June 2002.

TEST AIRCRAFT INSTRUMENTATION

During Phase 1 testing, the mission computer (MC) operational flight program (OFP) was not capable of providing the required TAWS inputs. Making a change to the MC OFP to do this testing would have been both costly and time consuming, especially when interface changes may have been required during development testing. To conduct flight testing without requiring MC software changes, the Navigation Avionics Platform Integration Emulator (NAPIE) system was used to provide in-flight simulation of altitude to the aircraft mission computers. The NAPIE system fed the resident MCs the altered elevation data to create the artificial raising of the terrain to provide the safety buffers. This resulted in testing in relatively close proximity to the ground with safety buffer altitudes that caused TAWS to believe the aircraft was lower than the actual flight condition. The NAPIE system provided a multitude of functions to create this necessary interface between the new TAWS functionality in the DMC and the rest of the host-aircraft's avionics. Initially, NAPIE collected the aircraft location and attitude input data required by the TAWS algorithm. Next, it re-packed the data into a set of newly defined data bus messages and sent the messages to the DMC. Subsequently, it polled the DMC for the newly defined TAWS output messages. Next, it forwarded flight test data and any TAWS alerts to the displays. Finally, it recorded data for post-flight analysis. NAPIE usage became obsolete on second and subsequent flight test phases as the altitude buffers became settable via the flight test pages. The flight test pages were already resident in the mission computer software configuration set and no re-writing the MC OFP was required.

USE OF SIMULATION

Ground based flight simulation was an absolute requirement for the testing of TAWS. First, the proper functionality of the TAWS algorithm was tested in a risk-free, controlled environment. Second, test plan projections of in-flight TAWS warning altitudes were verified with an external and independent TAWS truth model. Third, stimulation of the TAWS algorithm with previous GPWS flight test data was used for a performance comparison with GPWS and evaluation of improvements incorporated in TAWS. Fourth, both test pilots and test safety pilots flew the test profiles in the simulator for familiarity and risk reduction prior to actual flight test. Fifth, pilot proficiency in TAWS test maneuvers was maintained during delays between test flights and phases. Sixth, following flight test re-stimulation of the simulator with actual TAWS flight data was conducted to complete regression testing and identify problem areas more accurately. As a result, prior to the first flight test of TAWS over 500 hours of simulation development, testing, and training were conducted.

MAXIMIZING SAFETY

There was a heightened sense of awareness of Safety during test planning. The desire to have the aircraft tested as close to the ground as possible for accurate aircraft performance and pilot perception was delicately balanced with how much of an altitude buffer was required during CFIT protection testing. Due to the fast paced nature of the testing so close to the earth, it was decided the ground support team should include a separate safety observer external to the data collection and monitoring effort to provide the essential additional layer of safety for risk reduction. Additionally, specially designed displays were developed for both the test conductor and safety observer. The displays integrated real-time critical flight parameters and tolerances without the need to decipher strip charts or digital readouts. An example of the safety observer's display is presented in figure 7.

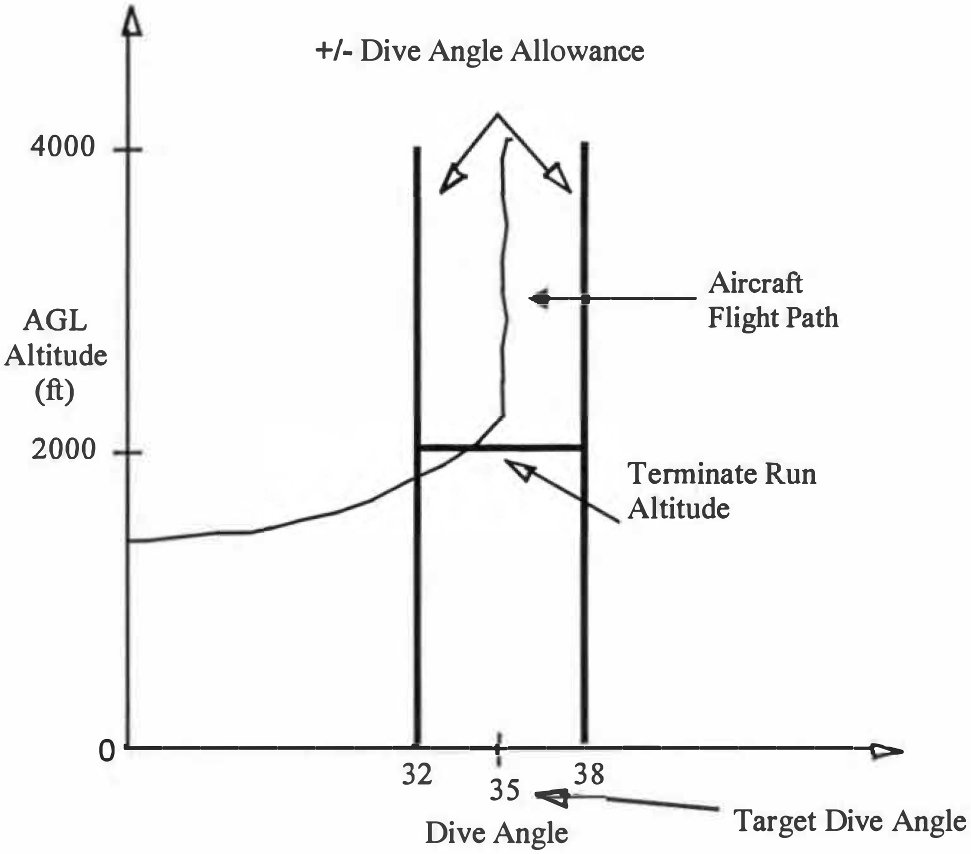

Figure 7
TAWS SAFETY OBSERVER DISPLAY

CHAPTER 5

TAWS FLIGHT TEST

TEST AIRCRAFT DESCRIPTIONS

The primary test vehicle for Phase 1 testing of TAWS was an F/A-18D, figure 8. A dual-crewed, twin-engine fighter/attack aircraft, the F/A-18D was also used for previous GPWS flight test. The F/A-18 Hornet first flew in 1978 and entered operational service with the U.S. Navy and Marine Corps in 1983.

The Hornet was originally built by McDonnell Douglas Aircraft which has since become part of the Boeing Company. The F/A-18 Hornet was the first tactical aircraft designed from the ground up as a true multi-role aircraft equally

Figure 8
F/A-18D HORNET
Photograph by the Author

capable in both air-to-air and air-to-ground mission roles. The aircraft is 56 ft long and has a wingspan of 38 ft. It weighs approximately 24,000 lbs empty and has a maximum takeoff weight of 51,900 lbs with full fuel and combinations of ordnance. Two General Electric F404-GE-400 engines rated at approximately 10,700 pounds military thrust and 16,000 pounds in maximum afterburner power the aircraft. As a fighter, the Hornet can carry heat-seeking Sidewinder missiles and radar guided Sparrow and Advanced Medium Range Air-to-Air missiles. As an attack aircraft, the Hornet can carry a wide variety of smart weapons, rockets, cluster munitions, air-to-ground missiles, mines and freefall bombs. The Hornet is capable of a maximum speed of approximately 1.75 Mach and a service ceiling of 50,000 ft. The Hornet has been exported to many countries and today sees service in Australia, Canada, Finland, Kuwait, Malaysia, Spain, and Switzerland. A more detailed description of the aircraft is contained in the F/A-18 A-D NATOPS manual.

The primary test vehicle for Phase 2 testing of TAWS was an F/A-18F, figure 9. A dual-crewed, twin-engine fighter/attack aircraft, the F/A-18F had not previously been used as a test aircraft for GPWS or TAWS. The F/A-18E/F Super Hornet first flew in the fall of 1995 and entered operational service with the U.S. Navy in the summer of 2002.

Figure 9
F/A-18F SUPER HORNET
Photograph Courtesy of the Boeing Company

The Super Hornet is built by the Boeing Company. The F/A-18E/F Super Hornet was designed as an affordable, more capable, more survivable, more lethal successor to the Heritage Hornet. Another true multi-role aircraft, the Super Hornet excels in both air-to-air and air-to-ground mission roles. The Heritage Hornet through upgrades throughout its lifetime has rapidly been reaching its limits for future growth while the Super Hornet provides the capability to embrace future hardware and software growth for the next projected 20 years.[12] The aircraft is 60 ft long and has a wingspan of 42 ft. It weighs approximately 32,000 lbs empty and has a maximum takeoff weight of 66,000 lbs with full fuel and combinations of ordnance. Two General Electric F414-GE-100 engines rated at approximately 13,900 pounds military thrust and 20,700 pounds in maximum afterburner power the aircraft. As a fighter, the Super Hornet can carry the same combinations of air-to-air missiles as the Heritage Hornet. As an attack aircraft, the Super Hornet can carry the same wide variety air-to-ground weapons but with an additional 2 wing pylon stations, it has a much larger payload capability. The Super Hornet is capable of a maximum speed of approximately 1.75 Mach and a service ceiling of 50,000 ft. The Super Hornet is currently only slated for service with the U.S Navy, but may see service with foreign countries in the future. A more detailed description of the aircraft is contained in the F/A-18 E/F NATOPS manual.

TAWS FLIGHT TEST MANEUVERS

The first flight of each test phase was dedicated to *functional* testing of TAWS. This started with verification of the altitude buffer settings and their proper operation. Next, an evaluation of the accuracy of the DTED data with aircraft positioning was conducted. Finally, verification of the graceful degradation of TAWS when DTED data was not present was required. Once functional testing was complete, testing during flight maneuvers could begin.

Low-level flight was conducted on standard visual navigation low-level routes at 500 and then 200 ft AGL to determine the extent of nuisance cues. These low-level routes are those same routes throughout the country in use every day by our military aircraft for tactical training. With successful results from the original low-level flight, low-levels were then re-flown at the same AGL altitude of 200 ft but with altitude buffers artificially raising the ground elevation. For these second low-level tests, the cockpit interface (pilot warning) was turned off resulting in TAWS operating behind the scenes. This produced a very large number of warnings recorded by the instrumentation for evaluation of TAWS performance without the large numbers of nuisance cues distracting to the pilot. No additional safety risk was added by subduing the TAWS warnings as all Hornets and Super Hornets currently conduct this type of training without TAWS installed in the aircraft. Low-level routes in the NAS China Lake operating area provided a much more mountainous region to test TAWS when compared to the routes in the east coast areas. Subsequently, the flight test data gathered during these low-levels was used to re-stimulate TAWS in the simulator to determine the accuracy of the warnings that were recorded. This technique permitted an evaluation of the effects of DTED errors on the warning altitudes and the potential for nuisance and/or late warnings.

Low Altitude Tactics (LAT) flying was conducted on the Patuxent River test range with real-time telemetry to evaluate the presence of any nuisance cues. LAT differs from low-level flight, as it is much more tactically aggressive. LAT employs terrain masking and demands maximum pilot performance to maneuver and maintain the aircraft down at the absolute minimum altitude. LAT flying utilizes a very strict set of dive recovery rules that gives the pilot exact dive angles and altitudes they use as gates to step down to the low altitude environment (approximately 200 ft AGL) in the most expeditious manner. Once in the low altitude environment, three-dimensional maneuvers are utilized to allow the pilot to practice reacting to defeat threat surface-to-air weapons and return as quickly as possible to the low altitude environment. LAT was the most demanding test for the TAWS system itself. Testing was conducted at speeds ranging from 400 to 500 knots in three-dimensional maneuvers pulling load factors of 4 to 5 all in close proximity to the ground. The LAT environment is highly dynamic flying and there is little time for TAWS to generate an effective CFIT warning if a potential condition were to develop.

Operationally representative minimum altitude *weapons delivery* maneuvers were performed at dive angles of 15 to 45 deg to evaluate the presence of any nuisance cues. During this testing normal weapons dive deliveries were conducted. The roll-in altitudes to start the simulated ground attack varied as the dive angles varied. For shallower dive angles lower roll-in altitudes were used. Normally the pilot initiates recovery from the dive at a predetermined minimum altitude in order to avoid a threat weapon system or weapons fragmentation effects. In this case, TAWS testing was conducted to assess its performance for the pilot that fixated on the target too long and did not initiate the pre-planned recovery. For TAWS testing, the aircraft recovery was delayed well beyond normal parameters with recovery only initiated at either the TAWS warning or the minimum weapons release cue (Break-X). The Break-X, a large X displayed in the pilot's Heads-Up Display (HUD), indicates there is insufficient altitude for the weapon to arm properly once released.

The final portion of the flight test was the most dynamic for the test aircrew and aircraft. This portion evaluated the *CFIT protection* and was conducted with various levels of safety altitude buffers to simulate the ground, as shown in figure10.

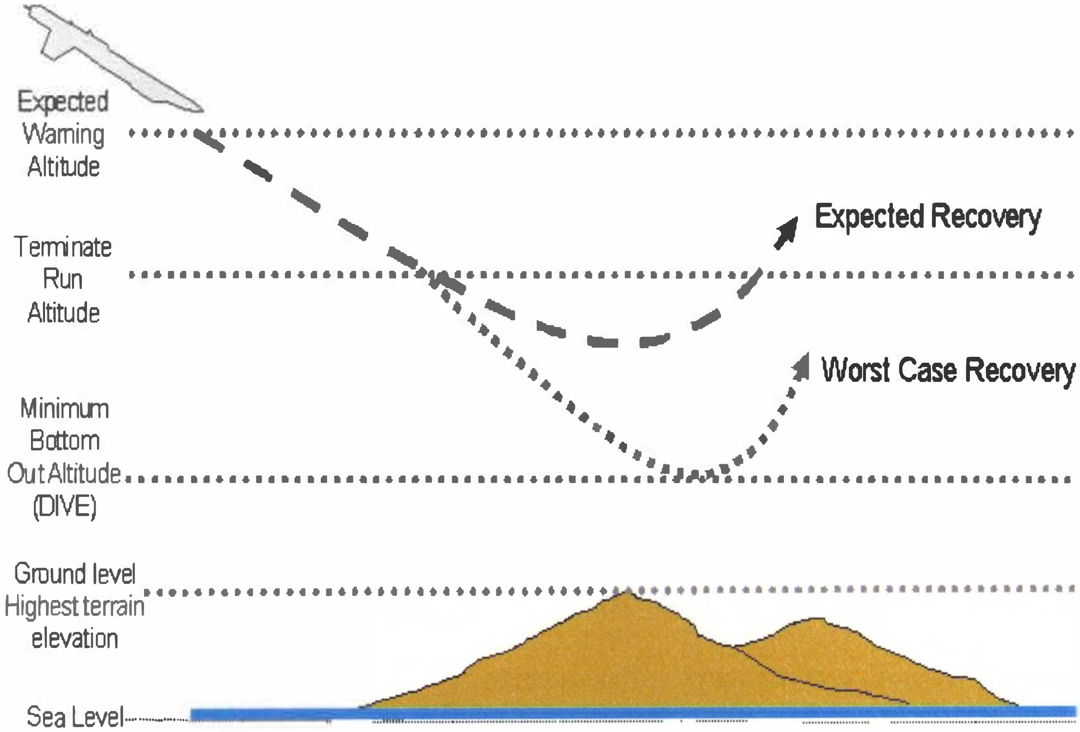

Figure 10
CFIT PROTECTION EVALUATION WITH SAFETY BUFFER

CFIT protection flights consisted of the Test Pilot in the front cockpit with a Safety Test Pilot in the rear cockpit. To enable a thorough evaluation of CFIT protection for the pilot who has had a loss of situational awareness, it was required the Test Pilot have little or no knowledge of the aircraft attitude and state prior to the warning. Prior to the test event, the Test Pilot closed his eyes, positioned his head away from the HUD (i.e. looking high over his shoulder), and conducted some mental task (i.e. count backwards from 100 by 4's). The Safety Test Pilot then maneuvered the aircraft to the test condition. Test conditions ranged from 150 KCAS to transonic airspeeds, level to 120 deg of roll attitude, level to downward 45 deg pitch attitude, and at aircraft gross weights varying from 29,000 to 51,000 lbs. At the TAWS aural warning, the Test Pilot opened his eyes and responded as quickly as possible to recover the aircraft – as if his life depended on it. The entire Test Pilot's response and recovery technique to the TAWS warning was measured. Reactions to warnings and handling of recoveries to include initial reaction, intuitiveness of the aural and visual cues, bottom out altitudes, load factor-onset rates, roll rates, and peak load factor were all evaluated. Test Pilot comments were also recorded on timeliness of warnings, Pilot-to-Vehicle Interface (PVI) issues and system operation. Any recoveries deemed a "Crash" (descent below altitude buffer or simulated ground) were evaluated real-time to determine applicability of further testing during that flight as well as further re-stimulation of that same maneuvers data in the simulator following the test flight.

FLIGHT TEST PHASES AND SOFTWARE CHANGES

PHASE 1 - DEVELOPMENTAL

Flight test of TAWS began on 5 Jul 00 at NAS Patuxent River, Maryland. F/A-18D flight test totaled 18.6 flight hours in 12 sorties.

Following Phase 1 flight test and evaluation of the data, TAWS entered a revision phase for the software. Changes incorporated for Build 2 or version 1.7 of the software included accounting for potential errors in the DTED in mountainous terrain, increase in pilot response time, and refinement of recovery trajectories. Most of the refinement of the recovery trajectories was focused on aircraft performance in the transonic region. The F/A-18 flight controls automatically implement a "G-Bucket" or a reduction in available load factor in the transonic region to preclude an overstress situation when encountering transonic longitudinal pitch-up. This refinement was aimed at correctly modeling the envelope of the "G-Bucket".[13] The Build 2 or version 1.7 was completed and ready for flight test in February 2001.

PHASE 2 - DEVELOPMENTAL

Flight test of Phase 2 - F/A-18F, NAS China Lake, was conducted October through January 2002. Flight test totaled 16.6 hours in 15 sorties. Phase 2 flight test was the first test of TAWS on the Super Hornet using all production hardware and software. Although flight test was conducted on a similar airframe in Phase

1, the Super Hornet had not conducted any GPWS or TAWS testing and therefore was considered a new airframe with a need for increased functional testing. Following the successful completion of the functional testing, nuisance and CFIT testing commenced. Once baseline performance was validated in the new airframe a reduction in the number of flight test events was possible due to the increased fidelity of the F/A-18 E/F simulation over the Heritage Hornet simulation. As NAS China Lake was a new test environment and new test aircraft for TAWS and the TAWS test team, there was added work in the creation of the TAWS real-time safety observer displays in a new telemetry environment as well as assimilation of F/A-18 E/F operations procedures.

Following Phase 2 flight test and evaluation of the data, TAWS entered the next revision phase for the software. Changes were incorporated for versions 1.8 and the final test version of 1.9. Improvements included incorporating a lateral stick predictor to better forecast bank angles as well as refine previous "G-Bucket" corrections. Flight test indicated that the previous "G-Bucket" modeling had been too conservative. TAWS was not accurately predicting what the Flight Control System was doing with the available load factor.[14] Available load factor modeling was changed and version 1.9 was ready for the Verification and Validation test phase in March 2002.

PHASE 3 – VERIFICATION AND VALIDATION

Flight test of Phase 3 - F/A-18D and F, NAS China Lake and Patuxent River, was conducted June through September 2002. Flight test totaled 7.7 hours in 7 sorties for the Heritage Hornet and 12.0 hours in 10 sorties for the Super Hornet.[15] Phase 3 flight test utilized all production hardware and software on both airframes under test. Phase 3 also was conducted completely with version 1.9 as the final developmental test software, the version proposed to go on to operational test.

CHAPTER 6

RESULTS AND LESSONS LEARNED

TAWS WORKS!

Test data from developmental and V&V testing indicate TAWS operated as designed and the design was good. The TAWS algorithm successfully and accurately incorporated DTED and aircraft positioning from GPS to provide timely cues to the aircrew. TAWS visual and aural cues were correct and with proper sensing. Warnings provided directive cueing that was not misinterpreted. Pilots were able to recover quickly and normally with slightly less altitude loss than was predicted. There were minimal nuisance cues during developmental phases and the V&V phase uncovered *no* nuisance cues. TAWS also demonstrated a high degree of reliability with no in-flight or in-aircraft failures noted.[15]

TESTING OF CFIT PROTECTION IS LIMITED WITH NAFOD (NO APPARENT FEAR OF DEATH)

The use of safety buffer altitudes during flight test greatly affects the pilot's perception of recovery. One cannot *see* the artificially raised terrain – "virtual ground", additionally the height above the buffer altitude is not displayed in the HUD. Therefore, during the recovery, the true proximity to the "ground" is not realized. Even in the simulator where the aircraft is flown without altitude buffers, the pilot knows that it is "just a simulator" and No Apparent Fear Of Death (NAFOD) is present. The NAFOD phenomenon is an issue during TAWS testing because the pilot tends to be more conservative during the recovery, which may lead to more "Crashes". The pilot may pay more attention to observing operational techniques and limits in order not to overstress the aircraft than would otherwise be done if indeed his life depended upon the recovery. In addition, pilots tend to be more aggressive during testing in the simulator due to NAFOD and lack of proprioceptive or 'seat-of-the–pants' cueing. This leads to problems when modifying the TAWS algorithms to eliminate the nuisance warnings – that is when they would not have been nuisance warnings if they had been received in flight. TAWS has been tested through the gamut of fleet representative maneuvers and nuisance cues have been virtually eliminated. It is anticipated that without the limitation of NAFOD (present during flight test), the fleet operator when confronted with a "real" TAWS warning of a potential CFIT condition and the accompanying adrenaline boost will exceed the ground clearance predicted by TAWS.

REQUIREMENT FOR WELL DEFINED ABORT CRITERIA AND BACKUP SAFETY REDUNDANCY

During all phases of TAWS testing there were no close calls or major safety concerns. This was mainly due to the detailed safety processes in place during the tests. Expected warning altitudes were calculated, verified, and tested in the simulator prior to flight. Terminate run altitudes were calculated and modeled based on aircraft performance in a worst-case recovery, completely independent of TAWS warnings. The Safety Test Pilot, Test Conductor, and Safety Observer all had independent views of the test event and communications enabling an abort of the event at any time. All efforts to reduce risk appeared to have been successful as dynamic flight test in close proximity to the ground was conducted safely.

USE OF SIMULATION FOR RISK REDUCTION AS WELL AS REDUCING PROGRAM COSTS

Simulation has been and will continue to be critical to the development and testing of TAWS even as TAWS moves on to other airframes for test. The Manned Flight Simulator at Patuxent River was the link between math models and integration into aircraft systems and hardware. Simulation validated these models as much as possible prior to flight test. Various test techniques were explored and subsequently refined in the simulator allowing identification of the most effective techniques for flight test. Test Pilots, Safety Test Pilots, Test Conductors, and Safety Observers were trained on TAWS and rehearsed the test events prior to conducting the events airborne. Once the simulation models were validated, actual flight test data was re-flown, or re-stimulated in the simulator, to allow for dynamic analysis without the requirement to re-fly the test thus reducing program costs.

NEED FOR AN ACCURATE DIGITAL TERRAIN ELEVATION DATA

For TAWS to work accurately, precise aircraft position and elevation of the surrounding terrain is a requirement. While GPS was able to place the TAWS test aircraft position within 50 m horizontally and 30 m vertically with level 1 DTED data, re-arced DTED was determined to be accurate only to approximately 138 ft (approximately 42 m) vertically. The DTED was required to be re-arced due to TAMMAC system requirements. TAMMAC requires that DTED gridposts must match one-for-one the pixels on the map display. This results in a re-arcing (under-sampling) of the gridpost locations existing in the DTED thereby changing the elevation accuracy.[16] DTED, for government use, is currently available only from National Imagery and Mapping Agency (NIMA) and most recent data utilizing various spheroid conventions is 1966, now 35 years old. Therefore, more up to date DTED is required to make TAWS as accurate as possible. Improved DTED should be available in December 2002 after the data from the Shuttle Radar Topography Mission (SRTM) conducted on the Shuttle Transport System Mission 99 (STS-99) is processed and released. This SRTM data will be at the DTED level 2 accuracy of 23 m horizontally and 18 m vertically. Yet even with the better data, as currently configured TAMMAC is incapable of improving due to the hardware constraints. TAWS warnings are only as good as the precise location of the aircraft in all three dimensions and the ability to compare that to the elevation at a precise location over the ground. Therefore, TAMMAC hardware will need to be improved to allow TAWS to reach its full potential.

SYSTEMS INTEGRATION OF AN ADDITIONAL AUDIO WARNING SYSTEM

The F/A-18 already incorporates a variety of aural warnings through an Amplifier Control, Intercommunication (ACI). The addition of TAWS resulted in a competition between existing aural warnings and new aural TAWS warnings. This is due to the existing system scheme where a currently playing voice cue cannot be interrupted and must play to completion. It was observed that if any existing aural warning was being presented, then the TAWS aural warnings were masked completely and only the visual HUD warning was presented to the pilot. As stated earlier, the aural warnings are the primary method of alerting the pilot. When confronted with an impending CFIT condition, there can be no other more important aural cues, to include the Radar Altimeter warning, than the TAWS warnings. If the aircraft inadvertently impacts the ground, the rest just does not matter. Therefore, the ACI needs to be modified to allow TAWS warnings to supercede all other aural warnings.

OBTAIN TEST SOFTWARE AS SOON AS POSSIBLE, FOR SINE DOES NOT EQUAL COSINE

As with most complex algorithms, simple errors can and do exist. Flight test software passed the safety-of-flight evaluation and rapidly began a compressed pre-flight test period. During simulation test and later flight test, intermittent nuisance cues were being presented when the aircraft was on southerly headings. It was determined that within the Build 1 algorithm, there was a cosine function when there should have been a sine function. This simple error was fully responsible for the nuisance cues. Ideally, if one can get software systems to a simulation evaluation early enough, small problems such as this can be identified in sufficient time to allow for a fix prior to flight test. Subsequent to Build 1, all software errors were identified and corrected in the laboratory and simulation environment prior to actual flight test.

PILOT RESPONSE TIME IS THE CRITICAL VARIABLE

The highly complex algorithm of TAWS is constantly computing not one but two recovery trajectories with a multitude of changing parameters such as airspeed, altitude, pitch rate, roll rate, vertical velocity, etc. The one constant in the equation is the set Pilot Response Time (PRT) value. This is the time that TAWS must back up from where it figures the aircraft response must be initiated back to the time the warning is presented to the pilot. Originally, the PRT was set at 1.0 sec. This resulted in 8 crashes and 39 saves. After re-stimulation of flight data and experimenting with varying the PRT, the PRT has been changed to

1.3 sec in Build 2. Simulation results indicate the new PRT will result in 3 crashes and 44 saves without any increase in nuisance rate.[10] Subsequent flight test indicated that the 1.3 seconds was the good compromise between warnings that were too early - 'nuisance' - and warnings that came too late – 'crashes'.

CHAPTER 7

FUTURE GROWTH AND PLANS

TAWS contains a generic algorithm and can therefore be tailored to any aircraft. Thus far it has only been tailored for and tested on the F/A-18, but any aircraft capable of installing a TAMMAC (or TAMMAC-like) system and GPS capability can make a predictive CFIT protection system a reality. For other U.S. Navy and Marine Corps aircraft slated to receive TAWS, testing should be slightly easier as TAWS conducted its first flight test on the most dynamic aircraft with the most widely varied flight envelope.

The possible incorporation of a pilot-selectable TAWS threshold option for low altitude flight is being considered. Currently the system provides only last-ditch warnings and assumes the aircraft can and will fly low altitude on every mission. In reality, low altitude training missions represent a small percentage of flights. With a low-altitude selectable option, CFIT protection can be improved by increasing the terrain clearance altitude in the algorithm for the majority of flights where there is no intent to go below a nominal 500 ft AGL except for landing.

Future growth capability envisioned for TAWS includes fusion of data from additional or improved sensors, obstacle avoidance, windshear detection, and monitoring of pilot responses to ensure sufficient corrective action is taken.[5]

The philosophy of "no nuisance warnings" allows for future development of an auto recovery capability within TAWS. An automatic recovery system must be nuisance-free (or very nearly) or the system is doomed to failure. The TAWS design includes "hooks" for automatic recovery of the aircraft. Further development is required for the flight control laws and TAWS commands before such a system can be tested. This requires, however, a paradigm shift in the CFIT protection approach from passive (pilot controlled) to active (automatic) aircraft recovery systems.

Incorporating the radar mapping of the earth data from the recent Space Shuttle Endeavor (STS-99/SRTM) mission will provide a much higher resolution database (DTED) to the TAWS algorithm. When it becomes available and with improvements in TAMMACs ability to process it, this highly accurate mapping data will provide the needed improvement to the DTED to allow TAWS to reach it's highest level of CFIT protection capability.

CHAPTER 8

CONCLUSION

The Terrain Awareness Warning System took its first flight in an ongoing effort to provide pilots who have lost situational awareness with the best possible cueing to avoid controlled flight into terrain. For the first time, Navy and Marine Corps aviators will have a robust, predictive system that provides CFIT cueing regardless of aircraft location, attitude, or radar altimeter function. Through the effective use of modeling and simulation, both the number of flight test events and risk, were reduced to manageable levels. Even though the testing of TAWS required flight test in close proximity to the ground, the use of Safety Test Pilots, additional safety observers, buffer altitudes and independent terminate run altitudes provided for a safe flight test period. TAWS stands complete with Developmental test and ready to begin Operational test in October 2002. Once complete TAWS will be poised to begin saving lives of operational F/A-18 aviators as well as be incorporated into many additional types of airframes throughout the fleet.

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VITA

Randolph J. Bresnik was born September 11, 1967. He grew up in Santa Monica, California where he graduated from Santa Monica High School in 1985. Attending The Citadel in Charleston, South Carolina, he graduated in 1989 with a Bachelors degree in Mathematics. Immediately following graduation he was commissioned a Second Lieutenant in the United States Marine Corps. After attending USMC Officer Basic School and Infantry Officers Course he began flight training, earning his 'wings of gold' in 1992. After receiving F/A-18 training, he was assigned to an operational F/A-18C squadron where he served in various rolls through over four years and three overseas deployments. While in the fleet he attended the USMC Weapons and Tactics Instructors Course (WTI) and the Navy Fighter Weapons School (TOPGUN). Returning stateside, he attended the USMC Amphibious Warfare School before being selected for U.S. Naval Test Pilot School. As a test pilot he served at the Naval Strike Aircraft Test Squadron in Patuxent River, Maryland on various F/A-18 A-F projects. He has also served as a fixed-wing and systems curriculum instructor at the U.S. Naval Test Pilot School. He is currently serving as the F/A-18 A-F platform coordinator at the Naval Strike Aircraft Test Squadron. He is also a member of the Society of Experimental Test Pilots. In November 2002, he will be joining a fleet F/A-18 squadron at Marine Corps Air Station Miramar, California.