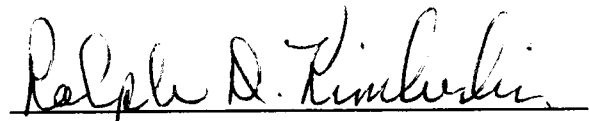


To the Graduate Council:

I am submitting herewith a thesis written by Gregory W. Carter entitled "Controlled Flight Into Terrain: Human Factor Causes and Technology Cures." I have examined the final copy of this thesis for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Masters of Science, with a major in Aviation Systems.

  
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Associate Vice Chancellor  
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**Controlled Flight Into Terrain:  
Human Factor Causes and Technology Cures**

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

Gregory W. Carter

December 1998

## **DEDICATION**

This thesis is dedicated to those who have always been there to support me: God, family, and friends. To my Lord Jesus for blessing me in this life and for the hope and peace of knowing that my relationship with Him is what is really important. To my wife Lee, and daughters Haley and Hannah, for their never-ending love and support. To my Mom, Dad and Grandparents for their love and encouragement. To the many wonderful friends I have made in my academic and professional journey, but most of all, to the ones who have given their lives in service to this country.

## **ACKNOWLEDGMENTS**

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## **ABSTRACT**

Many aircraft systems have been implemented to improve the pilot's orientation and awareness with respect to the terrain. Current Ground Collision Avoidance Systems (GCAS) and ground proximity warning systems have limitations that prevent protecting a severely disoriented or incapacitated pilot, for example, during G-induced loss of consciousness. This thesis will review human factor issues and causes relating to Controlled Flight Into Terrain (CFIT), analyze current and future GCAS technology in modern military and commercial aircraft, and present solutions to CFIT based on the author's research and flight experience in respect to this topic. This includes technology encompassing a combination of digital terrain mapping, improved situational awareness displays, and auto fly-up capability.

Reports of aircraft accidents in both military and commercial aviation continue to come in almost monthly, however, human physiology and the laws of nature are not going to change. The technology is available to counter the tragic consequences of unintentionally flying into terrain. Aircraft system designers as well as appropriate political, military, and corporate leadership have the responsibility to use emerging technology to minimize or eliminate future CFIT accidents.

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## LIST OF ABBREVIATIONS

|       |                                                 |
|-------|-------------------------------------------------|
| AFTI  | Advanced Fighter Technology                     |
| AGL   | Above Ground Level                              |
| ALOW  | Altitude Low Warning                            |
| ATA   | Air Transport Association                       |
| CARA  | Combined Altitude Radar Altimeter               |
| CFIT  | Controlled Flight into Terrain                  |
| DBTC  | Database Terrain Cueing                         |
| DTC   | Data Transfer Cartridge                         |
| DTS   | Digital Terrain System                          |
| EGPWS | Enhanced Ground Proximity Warning System        |
| FAA   | Federal Aviation Administration                 |
| GCAS  | Ground Collision Avoidance System               |
| GLOC  | G-induced Loss of Consciousness                 |
| GPWS  | Ground Proximity Warning System                 |
| HUD   | Head-Up Display                                 |
| MTC   | Minimum Terrain Clearance                       |
| PGCAS | Predictive Ground Collision Avoidance<br>System |
| SD    | Spatial disorientation                          |
| TCH   | Terrain Clearance Height                        |
| TRN   | Terrain Referenced Navigation                   |
| USAF  | United States Air Force                         |
| VMC   | Visual Meteorological Conditions                |

## INTRODUCTION

During the 10-year period 1987-1996, Controlled Flight Into Terrain (CFIT) was the largest single cause of airline fatalities worldwide, accounting for 36 out of 136 total accidents and 2,396 out of 7,484 fatalities. In 32 percent of the commercial jet aircraft CFIT accidents for the period, late warning or improper pilot response was a factor. Another 38 percent involved no warning, and in 30 percent of the cases, the aircraft was not equipped with a ground proximity warning system (GPWS).<sup>1</sup> When aircrew fly a mechanically sound aircraft into the terrain, a human factors cause quickly becomes the logical conclusion. From a military aviation perspective, human factors remain the most frequent cause of United States Air Force (USAF) major mishaps and the number one human factor cause is spatial disorientation (SD).<sup>2</sup> This often results in CFIT or ejection from a perfectly good aircraft.

This thesis begins with a review of human factors relating to aviation such as spatial disorientation and visual illusions. Then, current and emerging ground proximity warning systems and Ground Collision Avoidance Systems (GCAS) are presented and analyzed for their utility in guarding against human factors related CFIT. This includes an Enhanced Ground Proximity Warning System (EGPWS) the author had the privilege to evaluate during an Airbus A320 simulator evaluation at the United Airlines Training Center. Finally, this thesis presents a solution to CFIT based on the author's research and flight experience on this topic.

## **CHAPTER 1**

### **HUMAN FACTORS IN AVIATION**

#### **INTRODUCTION**

This chapter sets the foundation for the human factor issues involved in CFIT. With a basic understanding of human physiology, the designed technology cures and shortfalls can be better analyzed. Spatial disorientation, visual illusions, G-induced loss of consciousness and, misprioritized tasks will be discussed.

#### **SPATIAL DISORIENTATION**

Spatial disorientation (SD) has been a significant factor in at least 13 percent of all major aircraft accidents and 14 percent of all associated fatalities. These losses amount to over \$100 million per year, not to mention the sorrow and grief suffered by family members. Although the potential for spatial disorientation increased dramatically with the introduction of high performance, single-seat fighters into the Air Force inventory, pilots of multi-place aircraft are not exempt from spatial disorientation.

One definition of SD is a failure to correctly perceive one's attitude, motion, or position relative to the earth's surface or a known obstacle. SD may be unrecognized (type I), recognized (type II), or incapacitating (also known as vestibulo-ocular disorganization or type III). Unrecognized is more dangerous than recognized since the pilot is unaware that he has lost orientation and therefore he cannot correct the situation.<sup>3</sup> This could quickly develop into a CFIT mishap where the pilot or crew never knows there

is a problem until it is too late. Such a situation can quickly become fatal. With recognized SD, the pilot can cross check his "infallible" instruments and regain pilot orientation. With incapacitating SD, the pilot likely knows he is disoriented but cannot act due to an overwhelming physical or emotional stimulus (e.g. severe nystagmus or fear).<sup>2</sup> SD can be caused by various illusions associated with aviation. A basic understanding of the sensory systems, physiological mechanisms of various illusions, and conditions of flight where these illusions may be expected can give insight into the problems associated with SD.

### **ORIENTATION AND EQUILIBRIUM**

A person's orientation devices are located in both the conscious and subconscious sections of the mind. The subconscious mind uses sensory information from the ambient (or peripheral) visual system, the vestibular system and the somatosensory system to maintain orientation and equilibrium. This information is processed automatically at very high rates and without conscious effort. The conscious mind employs central (focal) vision to determine spatial orientation. In contrast to the speedy processes of the subconscious, information processed in the conscious mind is relatively slow, requiring active thought, and is normally very accurate. For earthbound activities, our subconscious orientation system receives adequate information from the sensory systems. However, when a person is subjected to the flight environment, these sensory systems are no longer totally reliable and may provide the subconscious with false information about its orientation in space. When flying without reliable external attitude or motion cues,

only the conscious mind with focal vision provides true orientation information.<sup>3</sup> The organs of equilibrium are shown in Figure 1.

### ***Vestibular System***

The primary purpose of the vestibular system, shown in Figure 2, is to enhance vision. The vestibular system provides angular and linear acceleration information to stabilize the eyes when motion of the head and body would otherwise result in blurred vision. The second purpose, in the absence of vision, is to provide perception of position and motion. On the ground, the vestibular system provides reasonably accurate perception of position and motion. In flight, however, the vestibular system may not provide an accurate perception of orientation. To understand how this vestibular information can be erroneous, one must look at its two sensors: the semicircular canals and the otolith organs of the inner ear.<sup>3</sup>

### **Semicircular Canals**

The three semicircular canals on each side of the head are positioned at right angles to each other so that angular accelerations in any spatial plane (pitch, roll, or yaw) can be detected. The fluid within the semicircular canals moves relative to the canal walls when angular accelerations are applied to the head. This fluid movement bends sensory hair filaments in specialized portions of the canals, which sends nerve impulses to the brain resulting in the perception of rotary motion in the plane of the canal stimulated. Again, since the response characteristics of the semicircular canal system

evolved for our ground-based environment, peculiar errors may be induced in flight. For example, a very small or

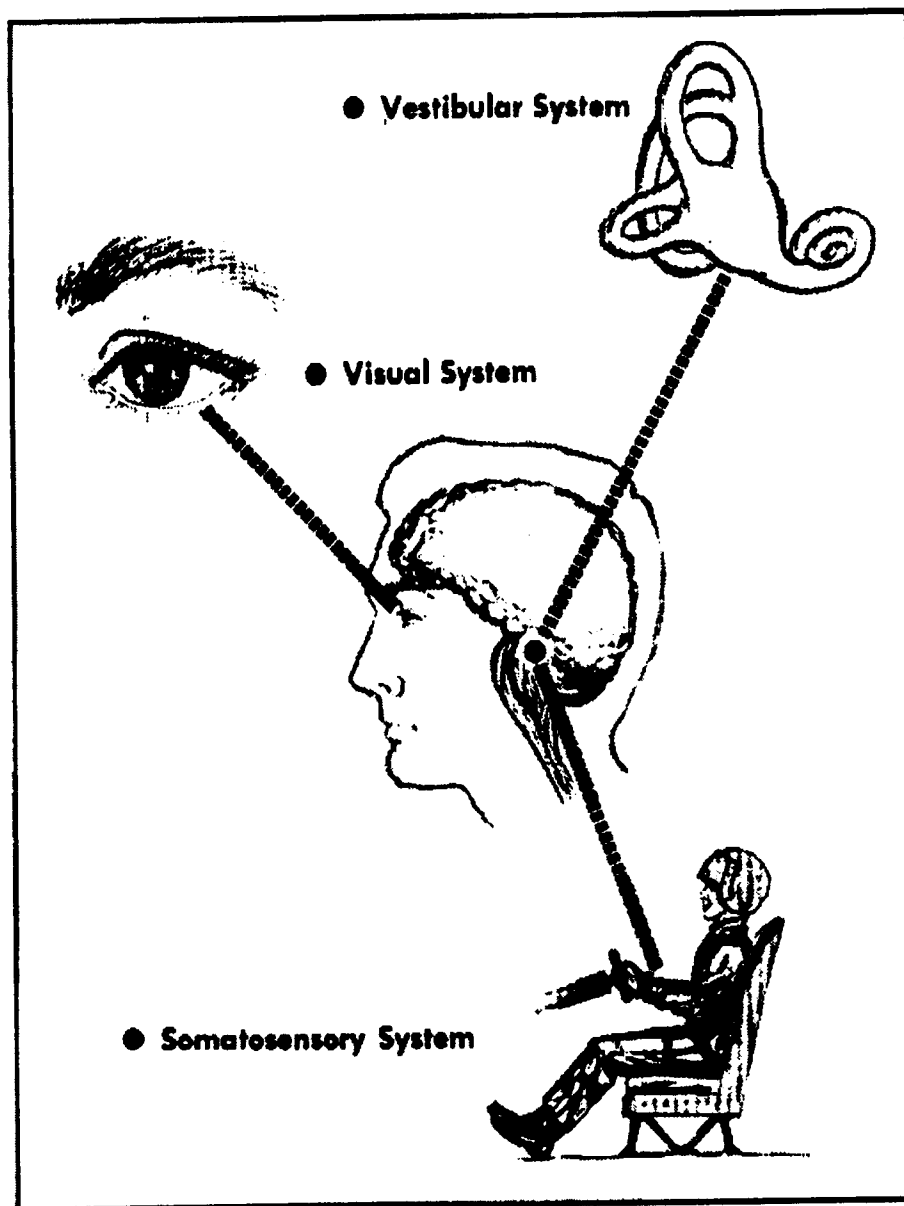


FIGURE 1 ORGANS OF EQUILIBRIUM

Source: *Instrument Flight Procedures*, Air Force Manual 11-217 Volume 1, Apr 1996.

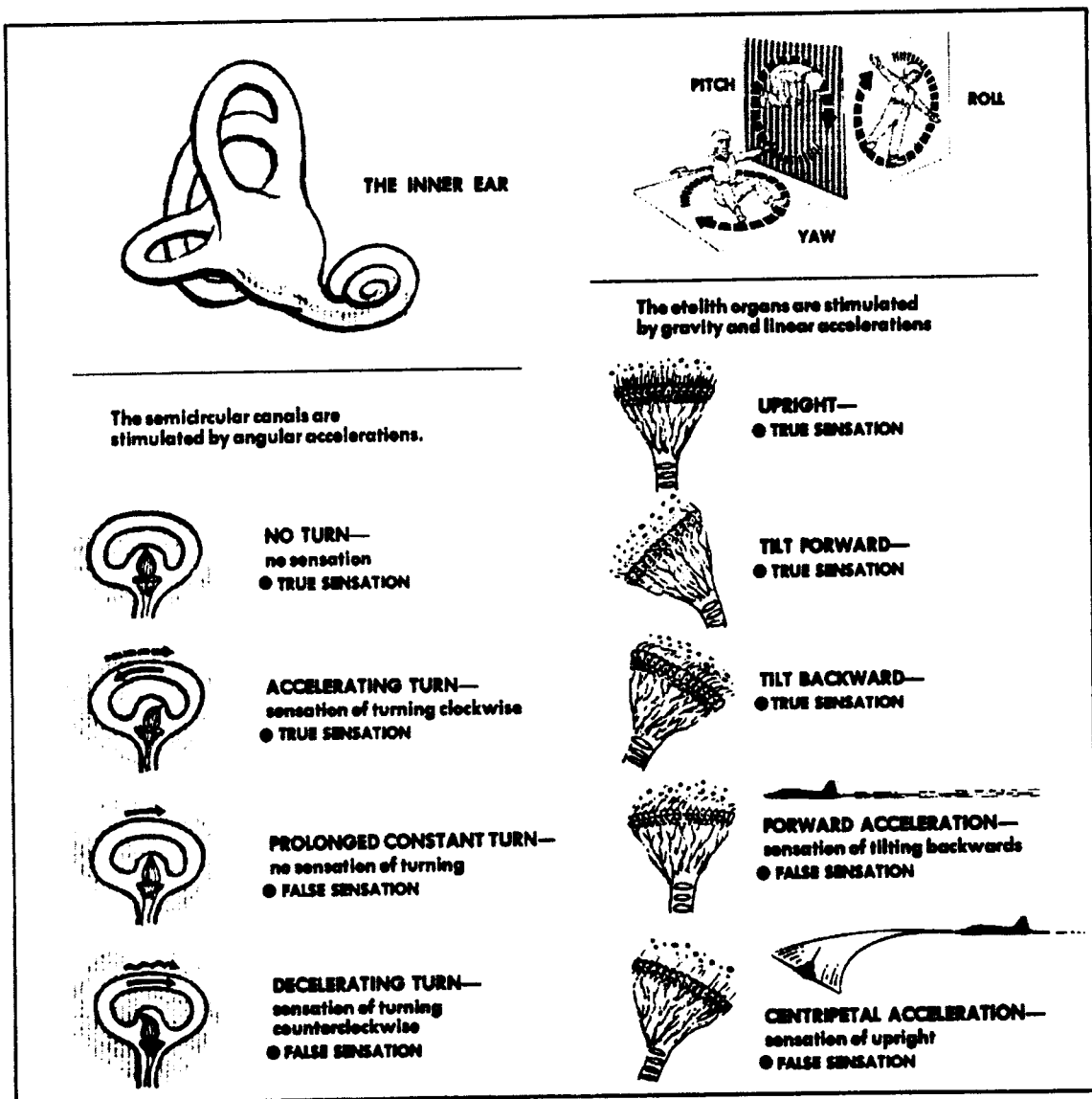


FIGURE 2 VESTIBULAR SYSTEM

Source: *Instrument Flight Procedures*, Air Force Manual 11-217 Volume 1, Apr 1996.

short-lived angular acceleration may not be perceived, and the resulting angular velocity can cause large attitude changes to develop over time. Additionally, angular accelerations experienced in flight can be quite different from those experienced on the ground. Hence, we can erroneously interpret the sensations produced by the fluid movement in the semicircular canal.<sup>3</sup>

### **Otolith Organs**

In the presence of linear acceleration or gravity, the sensory hairs that penetrate the otolithic membranes are bent by the relative movements of the otolithic membranes over the underlying structures. This activity is transformed into nerve impulses to the brain which convey information about head position relative to true vertical (or the direction of the pull of gravity). During flight, inertial forces are combined with the force of gravity and act upon the otolithic membranes. The direction of this combined or resultant force is almost never the direction of the true vertical. During flight, if the brain monitors the position of the otolithic membranes to determine which way is “down”, the brain will be deceived a large portion of the time.<sup>3</sup>

### **Visual System**

Vision is by far the most important sensory system providing spatial orientation during flight. In the absence of vision, orientation would be derived solely from the less accurate vestibular or somatosensory systems, and these systems do not provide reliable motion and position cues in the flight environment.<sup>3</sup>

### **Visual Dominance**

Of great importance in minimizing the effects of SD is an understanding of the concepts of visual dominance and vestibular suppression. Visual dominance exists when the pilot receives through the eyes all the information used to maintain correct orientation. Vestibular suppression is the ability to suppress unwanted vestibular sensations and reflexes. A pilot's ability to accomplish vestibular suppression comes as a result of understanding why spatial disorientation occurs and through practicing visual dominance. Experience and proficiency make vestibular suppression easier.<sup>3</sup>

### **Ambient and Focal Vision**

The visual system is actually composed of two separate visual systems to provide different visual functions. The ambient (mainly peripheral) visual system is primarily concerned with the question of "where", thus providing us with spatial orientation. Because ambient vision is monitored at the subconscious level, its information is processed automatically at very high rates and without conscious effort. The focal (or central) visual system is primarily concerned with the question of "what", providing fine detail for recognition. For spatial orientation, focal vision provides visual cues for judgment about distance and depth, and retrieves information from the flight instruments. While focal vision operates with great precision and accuracy, it is processed in the conscious mind relatively slowly, requiring active thought.<sup>3</sup>

### **Visual Conditions in Flight**

During flight, the utility of external visual references varies with the quality of available visual information. Because of the dynamic relationship between visual information available and mission requirements (straight and level flight to aggressive maneuvering), SD is possible, under a wide variety of visual conditions.<sup>3</sup>

### ***Somatosensory System***

Buried in many body structures, including the skin, joints, and muscles, the somatosensory sensors provide important equilibrium information as they respond to pressure and stretch. The sensations they elicit are the pressing feelings that you experience when you sit or the sensations that enable you to know the relative positions of your arms, legs, and body. This system is commonly called the “seat-of-the-pants” sense because some early pilots believed they could determine which way was down by analyzing which portions of their bodies were subject to the greatest amount of pressure. As illustrated in Figure 3, the “seat-of-the-pants” sense is completely unreliable as an attitude indicator.<sup>3</sup>

### ***Auditory System***

The auditory response in flight is unique in that it is an acquired skill. Pilots learn early in pilot training that when the aircraft is going fast, there is more airframe/canopy wind noise, and when the aircraft is going slow, the noise level decreases. Thus, the pilot is able to grossly discern airspeed by the noise level in the cockpit. For some pilots, the first clue that they are disoriented is a mismatch between the sounds they expect to hear,



FIGURE 3 SOMATOSENSORY SYSTEM

Source: *Instrument Flight Procedures*, Air Force Manual 11-217 Volume 1, Apr 1996.

based upon their perceived attitude, and the actual "wind" noise present. However, some modern aircraft do not give a discernible noise change until at a very high airspeed.<sup>3</sup>

## **PHYSIOLOGICAL MECHANICS OF ILLUSIONS**

### ***Vestibular Illusions***

In the absence of adequate visual orientation cues, the inadequacies of the vestibular and somatosensory systems can, and generally do, result in orientational illusions. It is customary to discuss vestibular illusions in relation to the two components that generate the illusions--the semicircular canals and the otolith organs.<sup>3</sup> There are several illusions associated with instrument flight conditions that will not be discussed, but are detailed in reference 3. Emphasis will be placed on day, Visual Meteorological Conditions (VMC) illusions to include a new category illusion (G-excess) thought to be responsible for a growing mishap trend in low altitude tactical flying.

### **Somatogravic Illusion**

The otolith organs are responsible for a set of illusions known as somatogravic illusions. This type of illusion is the sensation of change in attitude when the otolith organs are stimulated by linear acceleration. A false nose high sensation can occur when an aircraft accelerates forward in level flight. This somatogravic illusion may be unrecognized if the pilot is not concentrating on the flight vector of the aircraft (i.e. looking forward). Correcting for this illusion during acceleration could cause the pilot to dive the aircraft into the ground.<sup>3</sup>

### *G-excess illusion*

Although not really a somatogravic illusion, the G-excess illusion does depend on otolith-organ mechanisms. The G-excess illusion is an exaggerated sensation of body tilt caused by a greater than 1-G force on the otolith organs. The additional G force (that amount greater than 1 G) increases the response of the otolith organs, causing the false perception (illusion) of an excessive amount of pitch or bank. When a pilot's head is facing forward in a G-pulling turn, the G-excess effect causes a false perception the aircraft has tilted backwards (pitched up). In the absence of overriding visual cues, the pilot can make dangerous attitude control errors to correct for the G-excess illusion. If the pilot is looking at the "9 o'clock level" position while in a left turn, the G-excess effect would create the illusion the pilot's direction of gaze is above the actual direction (i.e., the aircraft is in less of a bank than is actually the case). The pilot would compensate for the illusion by over-banking. Because of the G-excess illusion, the pilot may be in a bank somewhat greater than the perceived bank angle, and feel comfortable in it. The G-excess effect and the illusion of under-bank do not necessarily disappear as a result of the compensatory over-bank. The same phenomenon can occur repeatedly as long as the G load is maintained. Thus, even though the initial perceptual error may be small, the accumulation of erroneous compensatory control input can result in a rapidly developing severe over-bank and the accompanying earthward velocity vector.<sup>3</sup>

### **Nystagmus**

During and immediately after maneuvers resulting from particularly violent angular accelerations, such as spins and rapid aileron rolls, the vestibular system can fail to stabilize vision. The eyes can exhibit an uncontrollable oscillatory movement called nystagmus. This eye movement generally results in an inability to focus on either flight instruments or outside visual references. Rolling maneuvers are especially likely to result in visual blurring because of nystagmus. Normally, nystagmus ceases several seconds after termination of angular acceleration; but under conditions of vestibular dominance and high task loading, nystagmus and blurring of vision can persist much longer, even long enough to prevent recovery.<sup>3</sup>

### **Visual Illusions**

Visual illusions are a form of SD and can be broken down into two modes for visual processing, the focal (foveal) mode and the ambient (peripheral) mode. Generally speaking, focal vision is concerned with object recognition and ambient vision is concerned with spatial orientation. But some visual orientation tasks in flying required a great deal of focal vision, and such tasks can be made extremely difficult by illusions resulting from misinterpretation of focal visual cues.<sup>3</sup>

### **False Vertical Cues**

The false vertical cue illusion can occur when flying into gradually rising terrain. It is possible for the pilot not to perceive he is actually flying closer and closer to the ground. This can be hazardous unless detected by reference to instruments or having the

focal vision triggered by “ground rush” (a pilot term to describe being very close to the ground.) Flying over unfamiliar terrain composition is another visual illusion. This can result if a pilot is used to flying over large trees and then is flying in an area of small shrubs. A pilot will attempt to see the same picture he is used to and will inadvertently be flying hazardously low to the ground as depicted in Figure 4. Similar illusion potential exists due to slope or composition of terrain under the approach path to the landing runway or the width or slope of the runway itself.

A similar hazard is presented when flying over snow covered terrain, desert terrain, or open water where poor depth perception cues can cause a pilot to misjudge his height above the ground or water.

### **Hidden Hill Illusion**

The hidden hill illusion can occur by flying in hilly terrain with low sun angles. A closer, smaller hill can be hidden in the shadow of a more distant, larger hill as shown in Figure 5.

### **Vection Illusions**

A sensation of self-motion induced by relative movement of viewed objects is called vection. Such sensations are frequently illusory, and can be of linear (translational) or angular (rotational) movement. An example of a linear vection illusion is that of an adjacent automobile creeping forward at a stop light and creating the sensation that one's own vehicle is creeping backwards. In formation flying, such illusions are common.<sup>3</sup>

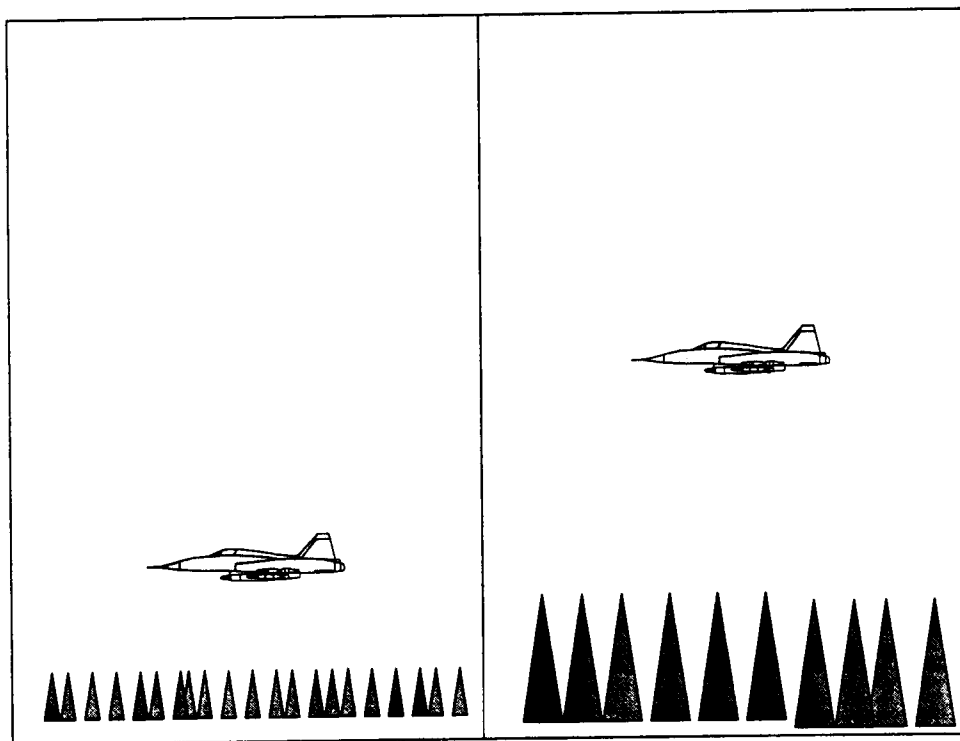


FIGURE 4 FALSE VERTICAL CUE ILLUSION

SOUTH WORTH  
PARCHMENT DEED  
100% COTTON FIBER

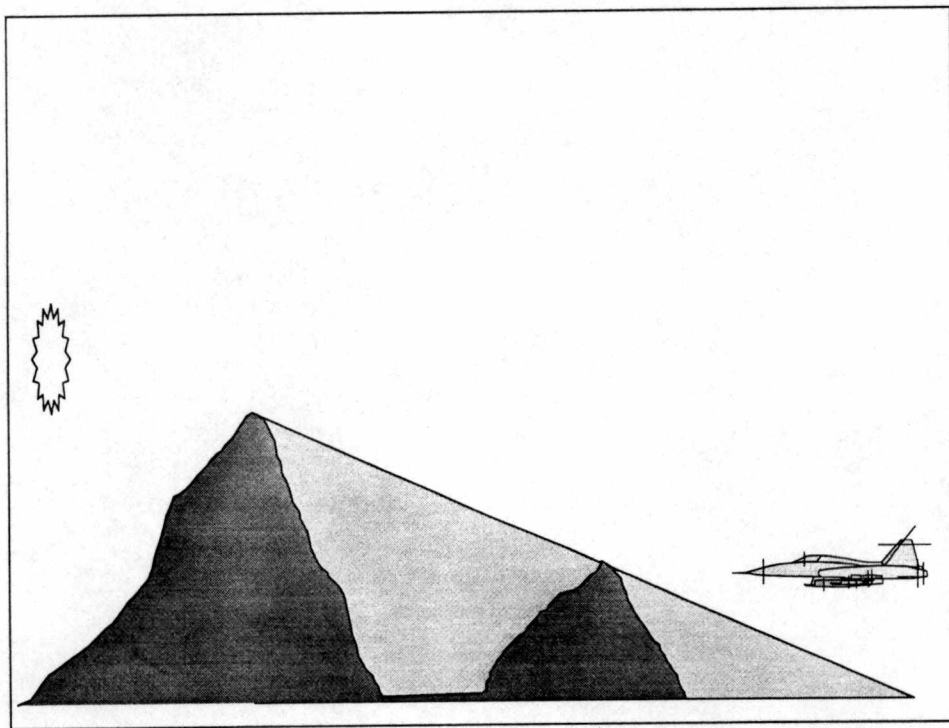


FIGURE 5 HIDDEN HILL ILLUSION

## *Somatosensory Illusions*

### *The Seat-of-the-Pants Sense*

Pilots can be deceived if they interpret the pressure sensations experienced during flight as meaning the same thing they would in an earth bound situation (i.e., pressure on the seat-of-the-pants indicates down). In flight, this pressure sensation is misleading because during coordinated flight, the force resulting from centripetal acceleration and gravity are always toward the floor of the aircraft. Thus, pilots can never tell through the pressure sensors which direction is the true vertical.<sup>3</sup>

## **G-INDUCED LOSS OF CONSCIOUSNESS**

We have reached the stage where fighter aircraft can exceed pilot tolerance for sustained high normal acceleration or G's. This capability often allows pilots to apply more G's than their body can tolerate; after a "short grace period," oxygen available to the brain is depleted and consciousness is lost. Pilots must anticipate G-onset, control the G-onset rate, and coordinate their G-straining maneuver. This requires mental discipline and practice to master. Failure to do so could spell disaster. G-induced loss of consciousness (GLOC) has two serious traits. First, it is more dangerous than other pilot stresses because it is not possible for the pilot to accurately and reliably know how close he is to the GLOC threshold. Secondly, since amnesia (of the incident) is a characteristic of GLOC, the pilot may never know that he has ever lost consciousness and may not be cognizant of any "close calls" he's lucky enough to have survived.<sup>4</sup> The bottom line is

that if there is not enough altitude or time for the pilot to regain useful consciousness, controlled flight into terrain is imminent.

## **MISPLACED PRIORITIES**

Misplaced priorities occur when a task is accomplished at the wrong place or time. Operating at low altitude is a hazardous proposition because it significantly reduces the time available to divert attention away from basic aircraft control while handling other tasks.<sup>4</sup> Channelized attention is a term used for mentally fixating on a single task. Task saturation is a term used for mental overload. The danger of channelized attention and task saturation is they divert attention away from the pilot's first priority - flying the aircraft. Cockpit tasking varies at different times throughout a low level route. It is important to establish priorities when mission tasking places more demands than time allows. Controlled flight into the ground is, in most cases, the result of misprioritization and task saturation. Regardless of assigned or perceived tasks, pilot distraction at low altitude is deadly.<sup>4</sup>

## **CHAPTER 2**

### **CURRENT GROUND COLLISION AVOIDANCE SYSTEMS**

#### **INTRODUCTION**

This chapter presents and analyzes current ground collision related systems in operation in modern aircraft. Many aircraft and associated systems were reviewed. For simplicity and consistency, most technical data presented is from the F-16 which is considered representative of most modern fighter and commercial aircraft. Specific human factor issues that the system addresses will be highlighted with strengths and limitations presented.

#### **HEAD-UP DISPLAY**

Most modern fighter aircraft and a few commercial or transport aircraft are now equipped with a head-up display (HUD). The primary situational awareness benefit of the HUD is the displayed flightpath marker and horizon line. However, The Air Force has still not certified the HUD as a primary attitude reference like other services and countries. A typical fighter HUD is presented as Figure 6. The HUD provides an extraordinary amount of information to the pilot and this information and the displays used to present it can provide several human factors issues.

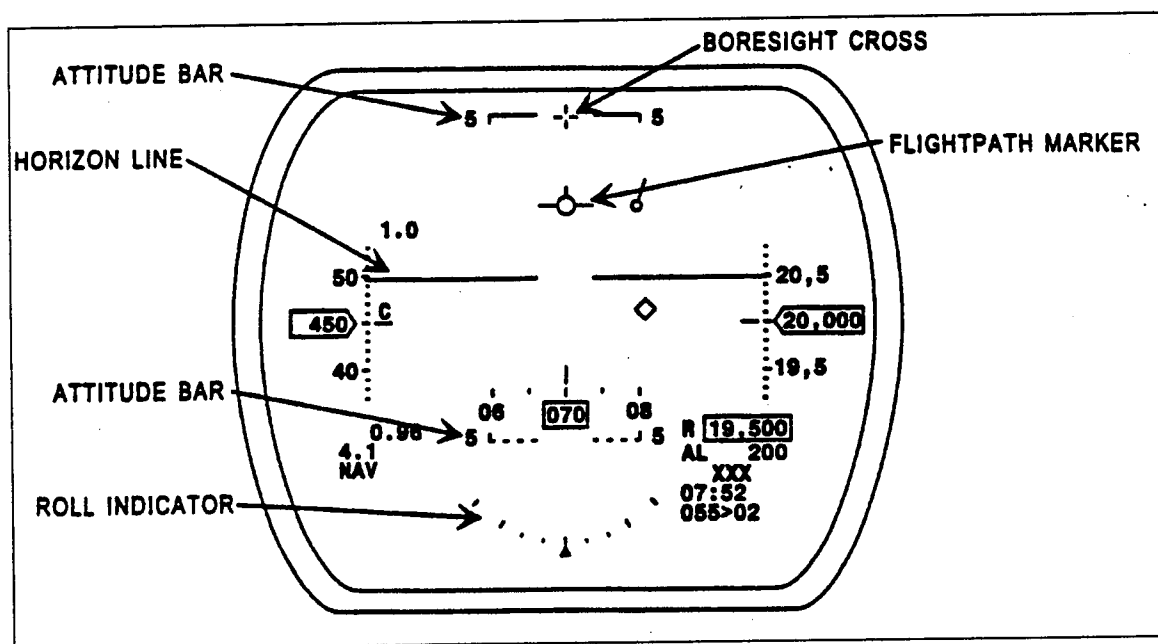


FIGURE 6 TYPICAL HEAD-UP DISPLAY

Source: *Head-up Display and Combined Altitude Radar Altimeter*, F-16 Pilot Training course Workbook, 14 Oct 96.

## **DIGITAL FORMATTING**

Digits, letters, and numerics require focal mode attention to read, and mental processing to decode and must be watched to provide trend information both for direction and speed.<sup>5</sup> Digital formatting does not provide a sense of how much further to go to reach a target parameter, commonly called trend data, nor does it provides boundaries for normal limits. Some design improvements have been made to enhance the trend capability like airspeed and altitude bars displays in addition to the digital read out. Overall, the HUD display forces the pilot to integrate all the information, resulting in increased time looking at the HUD information which can lead the pilot to missing other important sensory cues.

## **CLUTTERING**

Despite the proximity of the critical control parameters displayed on the HUD, the span of focus is too narrow to take it all in at a single eye stop. For example, in order to acquire attitude, airspeed, altitude and heading, one has to make four separate eye stops on the HUD. Though the clustering does enhance the crosscheck, it also clutters forward viewing.<sup>5</sup>

## **MESMERIZATION**

There is a tendency to stare at a certain portion of the HUD (e.g. the flightpath marker) while failing to monitor other critical parameters (such as airspeed or altitude) - all the while deluding oneself that one is in fact processing such information. Although the HUD symbology is collimated to infinity, the eye does not necessarily focus at infinity

when looking through the HUD. It may focus only on the surface of the combing glass, potentially degrading acuity for objects beyond. In flying low level, the potential for colliding with difficult-to-see objects such as power lines, guy wires, towers or leafless spiked trees is quite real. It is also perfectly possible for a tired pilot to stare at/through the HUD and fail to realize his aircraft is entering an unusual attitude.<sup>5</sup>

### **DISTRACTION POTENTIAL**

And finally, since one can see through the HUD, any motion beyond it or motion off the canopy can distract or cause SD in the form of avection illusion as discussed in chapter 1.<sup>5</sup>

The modern version of the HUD is an excellent design feature for maintaining visual dominance for today's pilot. The flightpath marker and horizon line are outstanding features to maintain aircraft attitude awareness and avoid illusions like somatogravic illusions. Some HUDs are being coupled with infrared sensors to penetrate darkness and millimeter-wave radar to pierce rain and fog.<sup>6</sup> Also, many of the GCAS warning indications are also presented in the HUD alerting the pilot of an impending hazardous situation. Even though there are minor drawbacks, one would be hard pressed to find a pilot that would rather not have the HUD. Future HUD designs will need to address the reliability for instrument flight and appropriate warnings that are presented if a self detected fault is identified.

## COMBINED ALTITUDE RADAR ALTIMETER

The typical combined altitude radar altimeter (CARA) is a radar altimeter which provides a very accurate reading of aircraft altitude Above Ground Level (AGL), maintains data communications with other subsystems, and provides an Altitude Low (ALOW) advisory function. It is used primarily for low altitude flying over flat surfaces and for adjusting personal visual judgment of actual altitude. In addition to supplying data for digital and analog readouts of radar altitude in the HUD, the CARA is also the source for the ALOW function. In a typical aircraft like the F-16, CARA ALOW provides voice and visual cautionary notification to the pilot regarding descent below a specified AGL altitude (ALOW setting). In flight, with the landing gear handle up, when the aircraft descends below the current CARA ALOW setting, the voice message, "altitude, altitude" is heard in the headset, and the HUD window containing the ALOW set altitude begins to flash as depicted in Figure 7. With the gear handle down in flight, as on final approach, the only CARA low altitude indication is the flashing of the ALOW set altitude window. The logic behind this is to avoid distracting the pilot with a voice message during landing approach. The CARA is certified up to 50,000 ft AGL, but is primarily used at low altitudes.<sup>7</sup> Figure 8 shows the pitch and bank limits of a typical CARA. The maneuvering limits are greatest at low altitude. The variable limits are due to an elongated beam shape and low power output. Invalid radar altimeter data should not occur when the CARA is operating properly and the pitch or roll limits of the system are not exceeded. If this occurs, the altimeter scales and the radar altimeter box goes

blank and the analog altimeter display in the HUD reverts to the barometric display if not selected.<sup>7</sup>

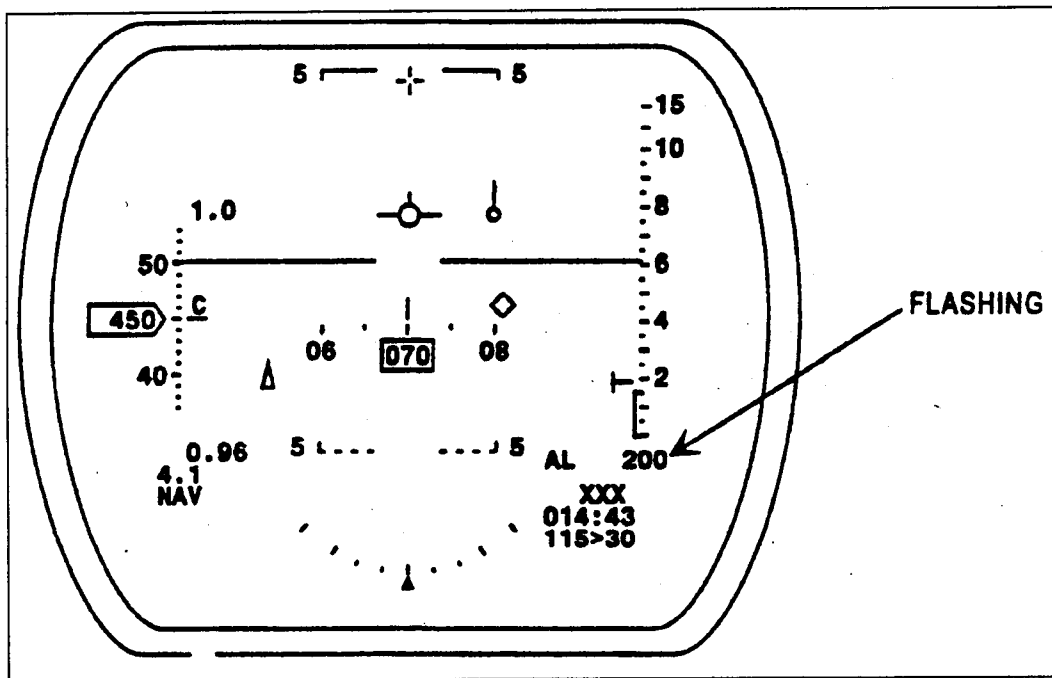


FIGURE 7 HUD CARA LOW ALTITUDE WARNING

Source: *Head-up Display and Combined Altitude Radar Altimeter*, F-16 Pilot Training course Workbook, 14 Oct 96.

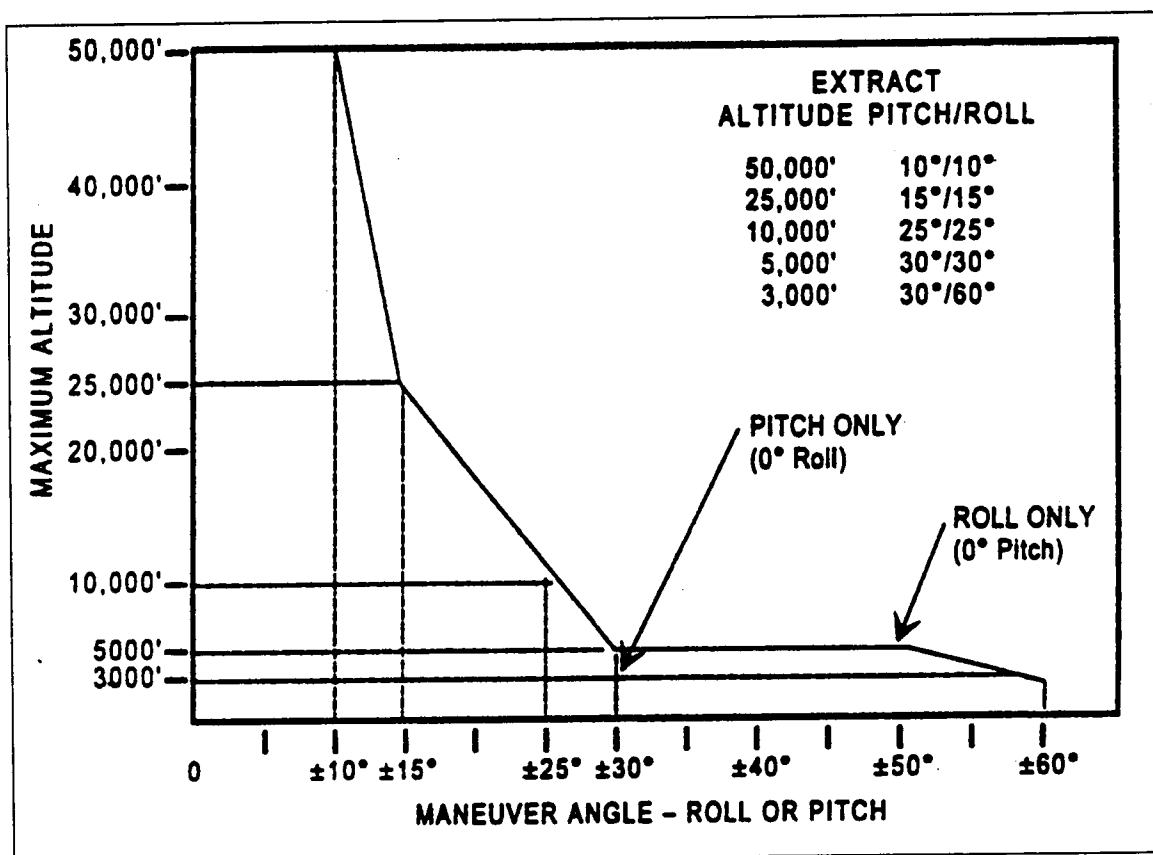


FIGURE 8 TYPICAL CARA PITCH AND BANK LIMITS

Source: *Head-up Display and Combined Altitude Radar Altimeter*, F-16 Pilot Training course Workbook, 14 Oct 96.

The CARA is a very beneficial system for low altitude navigation and has no doubt prevented many aircraft accidents. However, there are a few limitations that should be identified. First, most CARA's are unusable during aggressive maneuvering associated with fighter tactics. Hard turns greater than 2 G's (60° of bank) will result in no ALOW voice or visual warning. Secondly, the CARA is computing radar altitude directly below the aircraft and does not provide ground collision protection for terrain in the direction of the aircraft flight vector. This is especially hazardous during rugged terrain in conditions conducive to the "hidden hill" illusion. However, there is current flight test work of a radar altimeter offering 360 degree roll capability

#### **MEAN SEA LEVEL ALTITUDE SETTING**

Similar to the CARA ALOW setting, a barometric mean sea level altitude setting can be used as a minimum altitude during medium and high altitude operations (pilot selectable setting between 1,500 and 80,000 ft). This setting is referred to as the "line in the sky" and has obvious limitations in low altitude navigation in anything other than flat terrain.

#### **GROUND AVOIDANCE ADVISORY**

Ground avoidance advisory capability is made possible using existing aircraft avionics data and an assumed aircraft recovery algorithm. Ground clearance and breakaway cues then are used to provide an indication that the aircraft is in danger of a collision with the terrain. The advisory is activated when the avionics system is able to predict, with reasonable certainty, that the aircraft is in jeopardy of impacting the ground.

Upon execution of sufficient recovery maneuver, the advisory is terminated. The recovery algorithm in the F-16 assumes a 4 G wings level pull-up to preclude altitude lost during the dive recovery. Whenever aircraft weight, airspeed and/or external stores preclude the ability to reach 4 G's, the algorithm uses an estimate of maximum G available. The system predicts the altitude lost during the recovery maneuver and adds a "clearance buffer" of 50 ft as an added margin of safety. The computations assume level terrain and account for pilot reaction time, altitude lost during the roll to wings level, and G's available, but do not compensate for any negative G's during a wings level unload toward terrain. When the avionics system predicts that a collision with the terrain is imminent, visual and auditory advisories are activated.<sup>7</sup>

These advisories are:

1. Two seconds prior to reaching advisory altitude, a flashing "break X" symbol is displayed on each multi-function display. This advanced notice of imminent terrain collision in the event of heads-down cockpit activity. The two seconds is based upon a predicted time versus real-world.
2. Upon reaching the advisory altitude, a flashing break X symbol is displayed in the HUD.
3. Concurrent with the HUD break X, the voice message unit sounds "pull-up, pull-up".
4. In air-to-ground weapon delivery modes, the pull-up anticipation cue on the HUD moves towards the flight path marker preceding the initiation of the advisory sequence. When the pull-up anticipation cue intersects the flightpath marker, the

advisory sequence (items 2 and 3) is initiated. HUD and multi-functions display advisories are shown in Figure 9.

The most significant deficiency with the ground avoidance advisory function is the inability to clear the aircraft flight path into other than level terrain. This deficiency has been addressed with evolving digital terrain technology. There are additional night terrain following warnings that are not covered in this context.

### **DESCENT AFTER TAKEOFF WARNING**

The descent warning after takeoff function provides an aural warning indication of what may be an unintended dive/descent and possible ground collision condition within the first three minutes of flight (Figure 10). The voice message occurs only once per takeoff. The voice message "altitude, altitude" is issued when all of the following conditions apply:<sup>7</sup>

1. The landing gear is up.
2. The time since takeoff or touch and go with weight off wheels is less than three minutes.
3. The aircraft has gained 300 ft of altitude above the runway elevation, but has not yet gained 10,000 ft of altitude above runway elevation.
4. The present aircraft descent rate is such that, under present flight conditions, the aircraft will descend to the runway altitude within the next 30 seconds.
5. The message has not previously occurred since takeoff.

This function is useful to counter somatogravic illusions associated with instrument takeoffs. A dramatic limitation of this feature is evident if takeoff is made into rising

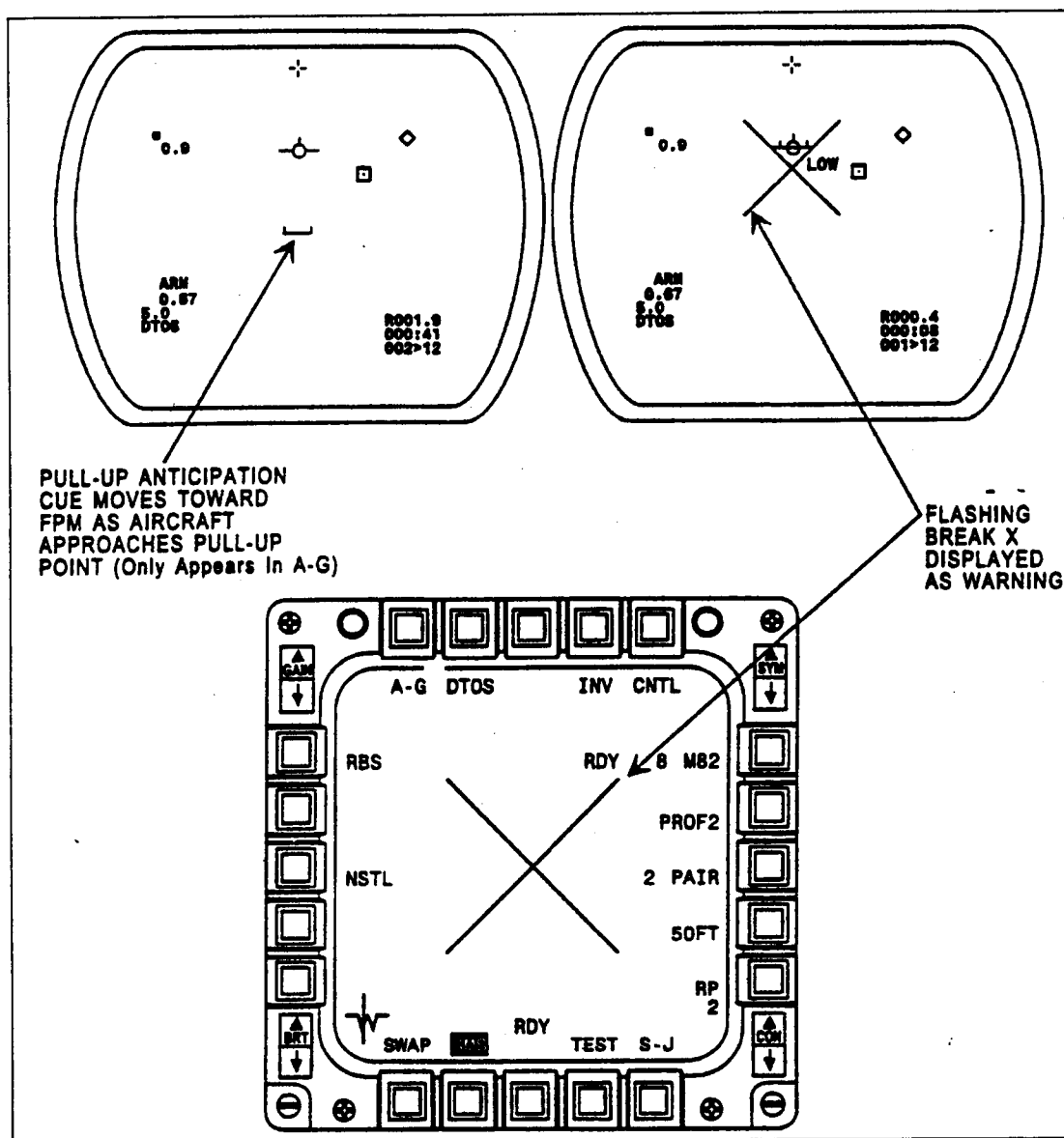


FIGURE 9 GROUND AVOIDANCE ADVISORY DISPLAYS

Source: *Head-up Display and Combined Altitude Radar Altimeter*, F-16 Pilot Training course Workbook, 14 Oct 96.

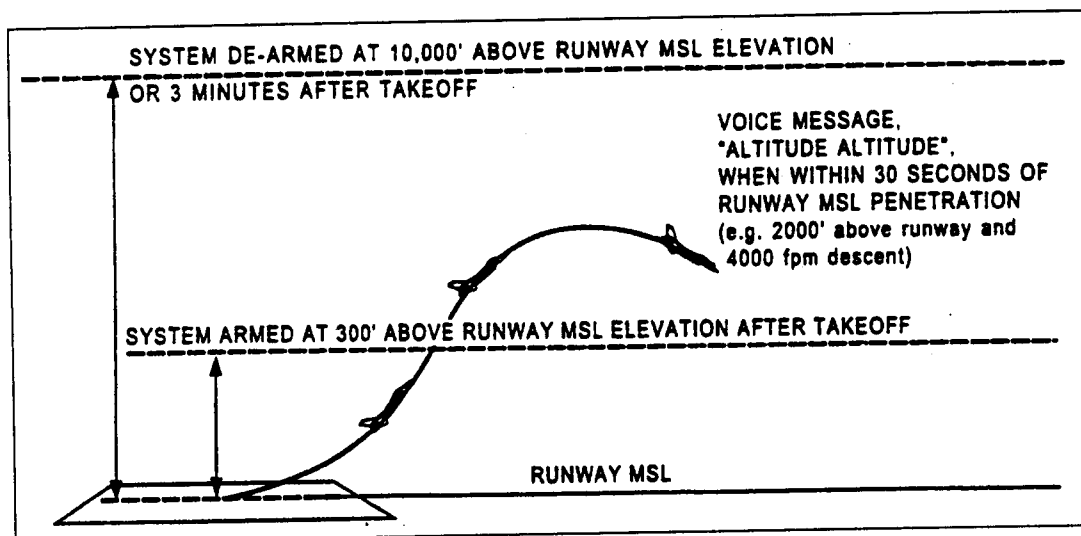


FIGURE 10 DESCENT AFTER TAKEOFF WARNING

Source: *Head-up Display and Combined Altitude Radar Altimeter*, F-16 Pilot Training course Workbook, 14 Oct 96.

terrain. Also, the 300 ft activation may not provide adequate protection during takeoff into low clouds or poor visibility.

## **DIGITAL TERRAIN SYSTEM**

Digital Terrain System (DTS) technology is being incorporated into many modern military and commercial aircraft. The F-16 DTS software is the British Aerospace Terrain Profile Matching System hosted in an upgraded data transfer cartridge (DTC) called the DTS/DTC. The DTS/DTC contains added memory for the digital terrain elevation data, vertical obstruction data, and the processor. DTS uses radar altimeter data and the stored digital data, along with information from the inertial navigation system (integrated inertial and global positioning system) to locate the airplane's position (X, Y, and Z) with respect to the digital map. DTS is primarily being incorporated to provide all attitude ground collision protection. However, it can also be used to provide obstacle warnings, navigation system updates, database terrain cueing, and passive ranging.<sup>8</sup>

## **TERRAIN REFERENCED NAVIGATION**

DTS needs to know where the aircraft is located with respect to the map so it can provide accurate Predictive Ground Collision Avoidance System (PGCAS) advisories. Consequently, DTS performs its own internal calculations, called Terrain Referenced Navigation (TRN) to determine aircraft position. The TRN function registers aircraft position relative to a terrain database stored in the DTS/DTC mass memory by estimating inertial navigation system errors using radar altimeter "observations" of the local terrain. These radar altimeter measurements or observations are correlated with the terrain

database to arrive at an estimate of aircraft horizontal (X,Y) and vertical (Z) position. The TRN function also estimates the accuracy of its own estimated horizontal and vertical positions and provides them to the F-16 core avionics in the form of horizontal and vertical position uncertainty data. Horizontal position uncertainty is TRN's assessment of the accuracy of its own X and Y position solution and can be thought of as a TRN Circular Error Probability (CEP). Vertical position uncertainty is the estimation of the linear accuracy of the TRN Z-axis solution and can be thought of as a "plus or minus" value. High and low horizontal position confidence is 120 and 200 meters respectively. High and low vertical position confidence is 6 and 12 meters respectively. Digital map and sensor uncertainties obviously need to be low when computing PGCAS algorithms. The pilot's primary interface with TRN is through status messages advising the pilot of how well it can support PGCAS.<sup>8</sup>

### **HUD ADVISORIES**

The highest priority advisories are displayed in the lower left corner of the Head-Up Display HUD as shown in Figure 11. The HUD window which is used to display the DTS advisories is the same one used for low fuel and trapped fuel warnings. Therefore, the various fuel and DTS messages have been prioritized based on their relative importance to the pilot. The following prioritized list briefly describes each HUD status message:

1. GND PROX (Ground Proximity) - Displayed when DTS PGCAS has been turned "on" and DTS issues a Ground Proximity warning. It is displayed concurrently with the HUD

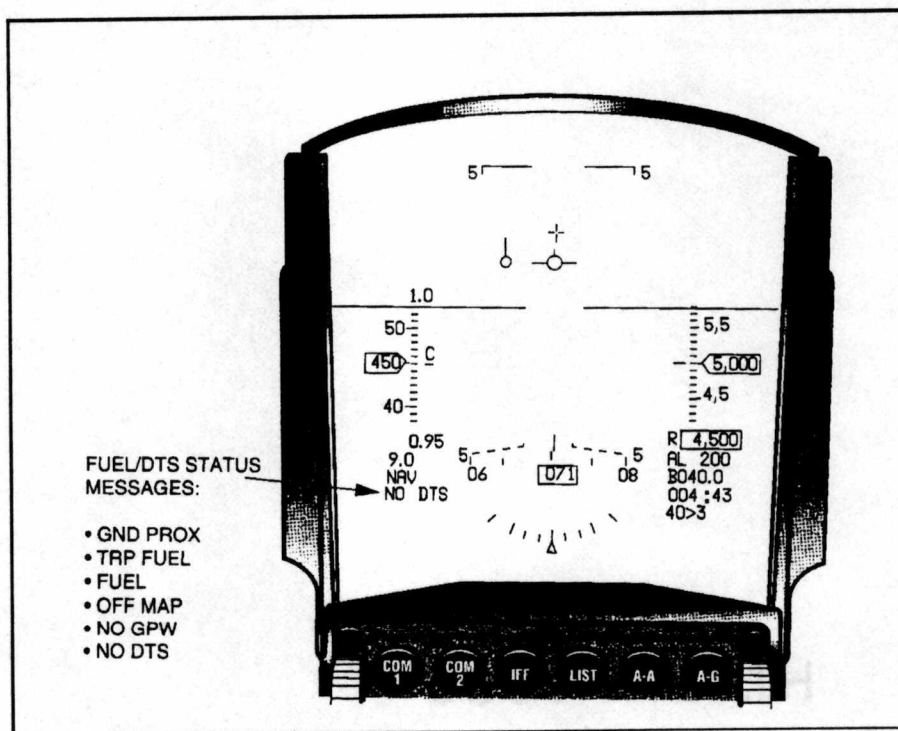


FIGURE 11 DTS HUD ADVISORIES

Source: C. Bergman, *F-16C/D Block 50/52 Production Tape No. 4 (50T4), The Pilot's Guide to New Capabilities & Cockpit, Enhancements*, Lockheed Martin Corp., 1997.

Break "X" ( a large flashing "X" symbol in the HUD).

2. TRP FUEL - Baseline trapped fuel advisory.
3. FUEL - Baseline present low fuel advisory.
4. OFF MAP - Displayed when DTS determines that the F-16 is off the DTS stored terrain database.
5. NO GPW (No Ground Proximity Warnings) Displayed when the DTS/DTC is operational but DTS determines that it cannot support the PGCAS function, or when the pilot has disabled the PGCAS function on the DTS Status Page.
6. NO DTS - Displayed when the DTS/DTC is installed in the cockpit, but the cartridge or DTS is not operational. The DTS/DTC must be present for this message to appear. This requirement prevents "NO DTS" from being displayed continually when a standard DTC is used.<sup>8</sup>

### **PREDICTIVE GROUND COLLISION AVOIDANCE SYSTEM**

The Predictive Ground Collision Avoidance System (PGCAS) provides advisories to the pilot when DTS determines that a ground collision is imminent. To provide this warning, DTS uses its stored terrain data to create a two dimensional "worst-case" terrain profile for 3 km (1.6 nautical miles) around the F-16's predicted flight path. If the aircraft's recovery profile is predicted to penetrate the pilot selectable Minimum Terrain Clearance (MTC) above the worst-case terrain profile, then DTS issues PGCAS warnings. Upon aircraft power-up on the ground, PGCAS defaults to mode-selected. However, if a power cycle occurs while airborne, the PGCAS selection resets to the last-

left state. The pilot can enable/disable the PGCAS warnings by mode selecting/de-mode selecting "PGCAS" on the DTS Status Page. When "PGCAS" is selected, the label highlights and PGCAS advisories are issued when appropriate. Conversely, when it is deselected, the label is not highlighted and PGCAS warnings are inhibited.

The default value at power cycles on the ground is 200 feet. However, the pilot can change the MTC to any value between 50 and 1,000 feet AGL. The pilot-selected MTC is used in all modes, except strafe and low angle dive bombing (which is defined in Air-to-Ground mastermode as, dive angle  $\leq 15$  degrees, calibrated airspeed  $\geq 375$  knots, and bank angle  $\leq 20$  degrees. In these modes, the PGCAS MTC is set to 50 feet to prevent nuisance warnings.

As shown in Figure 12, the PGCAS recovery profile includes two seconds for pilot reaction time plus time to roll wings level (at 115 deg/sec), and assumes a 4-G (total) pull-up maneuver. However, if the F-16 is loaded with more than 4-Gs when the advisories would be issued, the DTS uses the current G-load in the PGCAS computations. When DTS determines that the aircraft will penetrate the MTC, the avionics system notifies the pilot via both aural and visual cues. The concept is to provide ground proximity advisories in incremental steps. The PGCAS advisories occur as follows:

1. The Break-X begins to flash on the MFDs 1.1 seconds prior to the mandatory recovery point.
2. When the aircraft reaches the mandatory recovery point, the HUD Break-X begins to flash, "GND PROX" is displayed in the HUD DTS Status window (lower left side), and the voice message unit issues the "Pull-up...Pull-up" message.

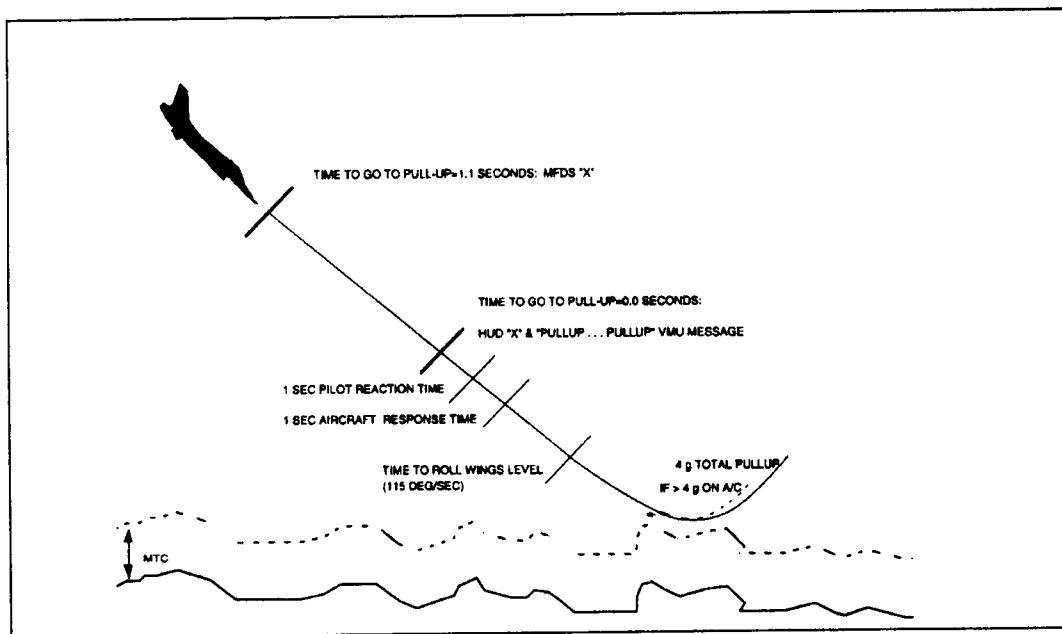


FIGURE 12 PGCAS RECOVERY PROFILE

Source: C. Bergman, *F-16C/C Block 50/52 Production Tape No. 4 (50T4), The Pilot's Guide to New Capabilities & Cockpit, Enhancements*, Lockheed Martin Corp., 1997.

PGCAS advisories are automatically inhibited when the landing gear is down and continue to be inhibited for 30 seconds after the gear has been raised. The advisories are inhibited during this time to prevent nuisance warnings during takeoffs and landings. The F-16 utilizes another system to warn against inadvertent descent after takeoff as previously discussed. PGCAS is also unavailable when any of the following conditions exist:

1. The F-16 is flying near the edge of the DTS stored terrain map and its flight path is predicted to take it off of the map.
2. The F-16 is off of the stored terrain map.
3. Terrain Referenced Navigation reverts to the Acquisition mode.
4. The INU data is invalid.
5. The aircraft is flying at greater than approximately Mach 1.0.

In the event that PGCAS is unavailable, DTS issues backup PGCAS advisories whenever the radar altitude is less than the MTC. In this case, the MFD "X," HUD "X," and "GND PROX" appear simultaneously.<sup>8</sup>

### **DATABASE TERRAIN CUEING**

Database terrain cueing (DBTC) is a vertical steering guidance function that aids the pilot in flying low level at a selected Terrain Clearance Height (TCH). DBTC improves a pilot's awareness of the terrain by providing a cue in the HUD. Using TRN position relative to the database, the DBTC function generates a worst case terrain profile by simulating a sensor scanning the terrain ahead of the aircraft as shown in Figure 13.

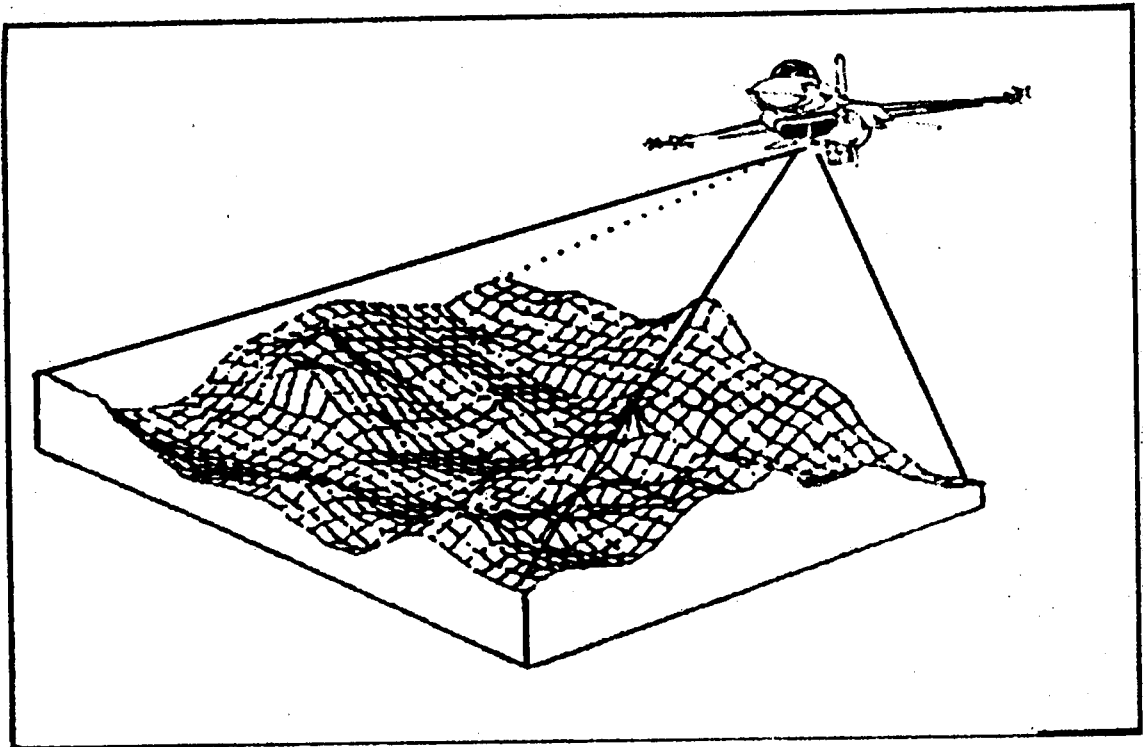


FIGURE 13 SIMULATED DATABASE TERRAIN CUEING SCAN PATTERN

Source: Christenson, Kevin, Weber, Gregory, Seebos, Michael, Gillen, Sean, *F-16 Database Cueing - An Investigation of Display Handling Qualities*, Society of Experimental Test Pilots Symposium Proceedings, 1997.

The scan area is adjusted to account for uncertainties in TRN position corrections. Additionally, the scan is shifted into a turn based on turn rate. With this scan area of the database defined, the final worst case profile is reduced to a two dimensional representation of the terrain contained in the scan area as show in Figure 14. The DBTC function then computes the normal acceleration or “G command” necessary to clear the terrain in the worst case profile by the pilot selected TCH within the limits of +2.0 to -0.9 incremental G’s. The end product of this DBTC calculation is a box displayed to the pilot in the HUD as presented in Figure 15.<sup>9</sup>

The emerging DTS technology is promising and has the advantage of not requiring a forward-looking sensor and having knowledge 360 degrees around the aircraft.<sup>10</sup> This may be very beneficial in military applications. However, there are a few drawbacks to DTS. First, not all aircraft have the computer or memory capability required for the digital terrain database. In addition, it is a requirement to have the flying area mapped and stored prior to flight. Also, current displays for the pilot are limited to HUD steering and warnings with no situational awareness presentation. Also, early flight testing presented some display and handling quality challenges. As the aircraft approached a peak, a late commanded climb resulted in the aircraft continuing to climb for several hundred feet more after crossing the peak, known as “ballooning.” From a military utility standpoint, these DBTC performance problems could degrade the pilot’s ability to terrain mask at a specified TCH. In addition to DBTC performance issues, pilots found the DBTC cue to be jittery and too sensitive when they attempted to follow

the cue as closely as possible. The jerky movement of the steering cue box was a big distraction which could divert the

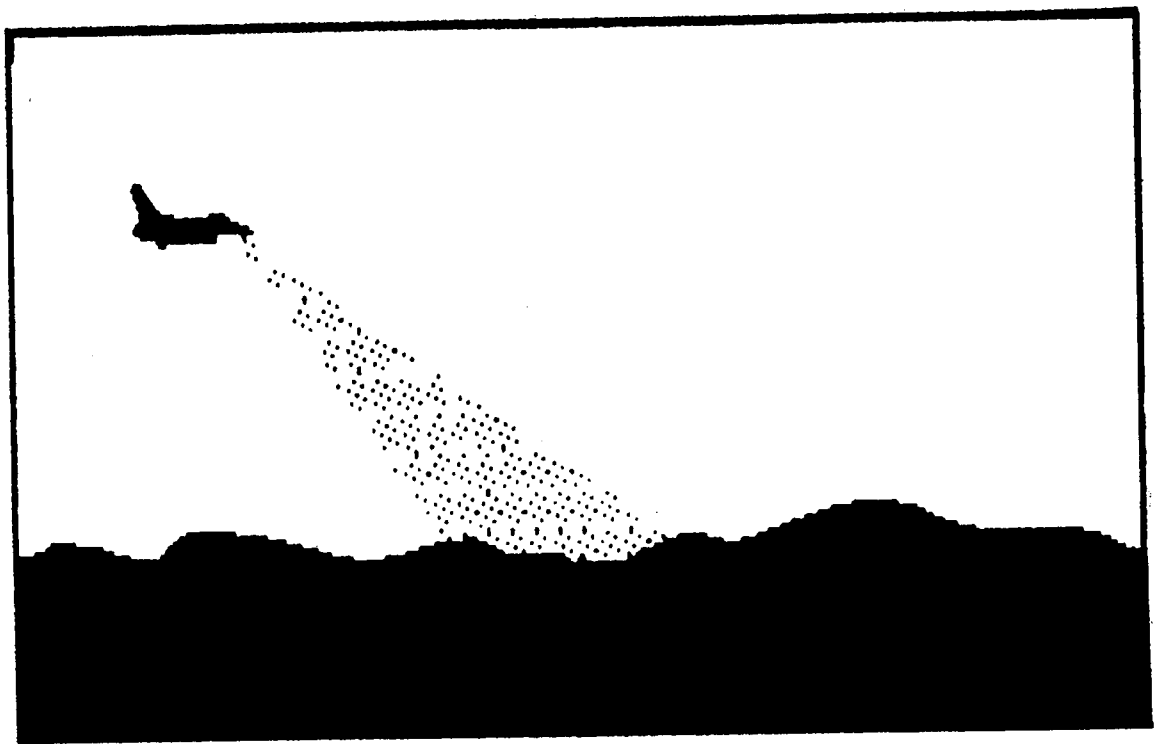


FIGURE 14 F-16 TWO-DIMENSIONAL WORST CASE DBTC PROFILE

Source: Christenson, Kevin, Weber, Gregory, Seebos, Michael, Gillen, Sean, *F-16 Database Cueing - An Investigation of Display Handling Qualities*, Society of Experimental Test Pilots Symposium Proceedings, 1997.

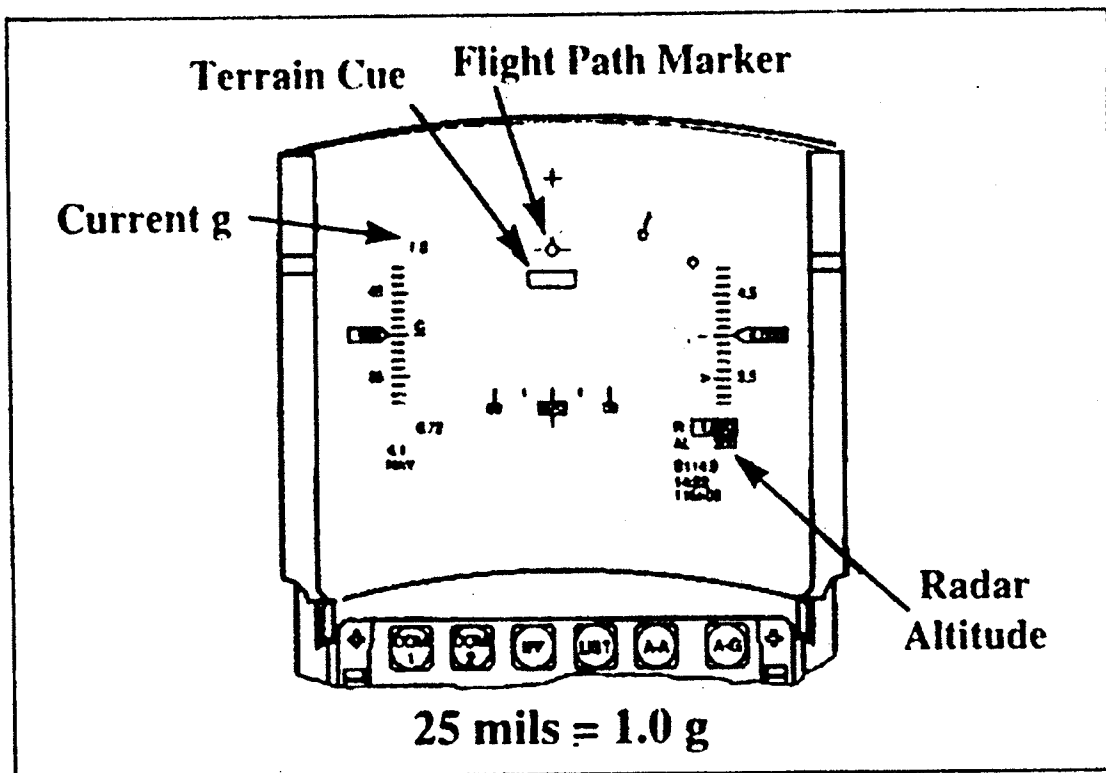


FIGURE 15 F-16 HUD DATABASE TERRAIN CUEING PRESENTATION

Source: Christenson, Kevin, Weber, Gregory, Seebos, Michael, Gillen, Sean, *F-16 Database Cueing - An Investigation of Display Handling Qualities*, Society of Experimental Test Pilots Symposium Proceedings, 1997.

pilot's attention away from the actual terrain. The pilot could do a better job of terrain masking by visually referencing the actual terrain. Most significantly, if a pilot did try to follow the box closely, flight safety could be jeopardized by a divergent pilot-induced oscillation that developed at various airspeed and terrain combinations.<sup>9</sup> Improvements to these flight test identified concerns are addressed in Reference 9. The biggest safety related disadvantages to DTS are the reliance on accurate aircraft navigation solution and absence of updated digital data for man made obstacles. Databases need to include manmade obstacles or a forward-looking system will be needed to provide adequate protection. Finally, this system does not protect the disoriented or GLOC pilot warranting some form of automatic recovery or fly-up capability.

## **CHAPTER 3**

### **FUTURE GROUND COLLISION AVOIDANCE SYSTEMS**

#### **INTRODUCTION**

The GCAS technology presented thus far has the common deficiency of requiring the pilot to respond to an audible or visual alert warning. Two systems will be presented that attempt to overcome this shortfall. The first is the Enhanced Ground Proximity Warning System currently being tested in United Airlines simulators and limited numbers of Airbus A320 aircraft. Then, an auto recovery GCAS system currently undergoing flight testing will be presented followed by a virtual interface cockpit concept.

#### **ENHANCED GROUND PROXIMITY WARNING SYSTEM**

In December 1997, the Federal Aviation Administration (FAA) and the Air Transport Association (ATA) announced jointly that ATA-member airlines will voluntarily install, by 2003, Enhanced Ground Proximity Warning System (EGPWS) equipment on approximately 4,300 airplanes. At the time of the announcement, about 175 airplanes had been so equipped. In addition, the FAA was expected to publish in early 1998 a notice of proposed rule making that would require EGPWS to be installed by 2003 in all U.S.-registered turbine-powered airplanes having six or more seats. These new initiatives follow closely the recommendations of the 1992 government-industry CFIT (Controlled Flight into Terrain) Task Force.<sup>1</sup>

A limitation of a conventional Ground Proximity Warning System (GPWS) is that it provides very short warning times when flying toward steeply rising terrain. That's because, for terrain alerts, GPWS uses only radar altitude, based on the radar altimeter "looking" straight down. Also, GPWS does not provide alerts for "landing short" situations, when the airplane is in the landing configuration and is descending at a normal rate, because the GPWS assumes the airplane will land at an airport.

The next generation of GPWS, "Enhanced GPWS" (EGPWS), which was developed by Allied Signal Aerospace, adds barometric altitude and airplane position, which the system compares to an onboard airport database and a terrain database, to provide look-ahead terrain alerting and a map display of the terrain color-coded to show layers of terrain at specified altitudes above and below the aircraft. The three main functions of EGPWS are the following: 1) terrain display for increased situational awareness, 2) voice alerts for terrain avoidance, comparing airplane flight path with the terrain database, and 3) alerts independent of landing configuration, comparing airplane position with the airport database (i.e., all hard-surfaced runways at least 3,500 feet long with a published instrument approach). All the other current GPWS modes (e.g., high sink rate, below glideslope, etc.) remain active.

The look-ahead terrain-alerting system includes a caution envelope and a warning envelope, both of which include look-ahead distance and an altitude offset. The terrain-alerting function's look ahead algorithms vary with groundspeed, flight path angle, rate of climb or descent, turning flight, and the distance to the runway. The terrain display uses

black, green, yellow, and red (in differing densities) to display terrain within specific altitude bands above and below the aircraft altitude.<sup>1</sup>

## **SYSTEM DESCRIPTION**

The EGPWS retains all the controls and functions of the current GPWS. In addition, improved low terrain warning during landing, a terrain display, and predictive terrain conflict alerts are provided. The EGPWS uses an onboard worldwide terrain database, Flight Management and Guidance Computer 1 position, and airplane altitude and track to display the proximity of surrounding terrain on the Navigation Display (ND).<sup>11</sup> All terrain from 2,000 ft below the aircraft to over 2,000 ft above is indicated.<sup>12</sup> The information is provided in a color scheme, which references the terrain to airplane altitude. Caution and warning alerts, both aural and visual, are given if the airplane approaches threatening terrain. The new terrain alerting functions of the EGPWS are independent of the current GPWS functions. Failure of the additional terrain features will not affect operation of the basic functions of the GPWS.<sup>11</sup>

### ***Terrain Clearance Floor***

The EGPWS database contains all runways more than 3500' in length, world wide, for which terrain data exists. A terrain clearance floor database is positioned for each runway to warn of premature descent below the floor regardless of airplane configuration. If the airplane descends below the altitudes shown, a "TOO LOW TERRAIN" aural warning is annunciated until the airplane ascends above the floor. In addition, the red GPWS light, located on each pilot's will illuminate until the alert

envelope is exited.<sup>11</sup> An example terrain clearance floor envelope or aircraft position versus airport location database is shown in Figure 16.

### ***Background Terrain Display***

When the terrain display is selected on the ND, background terrain is depicted as variable density dot patterns in green, yellow and red. The density and color of the patterns are a function of the height of the terrain with respect to the altitude and rate of descent of the airplane. In areas of the world where terrain data is not available, magenta is displayed. Presently, in all areas where the A320 is flown, accurate terrain data is available. The EGPWS density and color of the patterns are shown in Figure 17 and an example ND display is shown in Figure 18.

### ***Predictive Terrain Alerts***

When maneuvering close to terrain, the “look ahead” distance for cautions and warnings is a function of ground speed and turn rate. This helps to avoid alerts based solely on the straight-line distance to the terrain. For approaches into airports with surrounding high terrain, the alert envelopes are modified to allow normal approach maneuvering without nuisance alerts. In addition, on approach and departure, the altitude above runway elevation, which generates a terrain alert, is a function of the range from the airplane to the nearest runway threshold. This prevents undesired alerts during takeoff and landing.<sup>11</sup> The following predictive terrain alerts are issued:

- Caution Alerts - Approximately 40-60 seconds prior to a potential terrain conflict, a caution alert, consisting of the aural “CAUTION TERRAIN, CAUTION TERRAIN,”

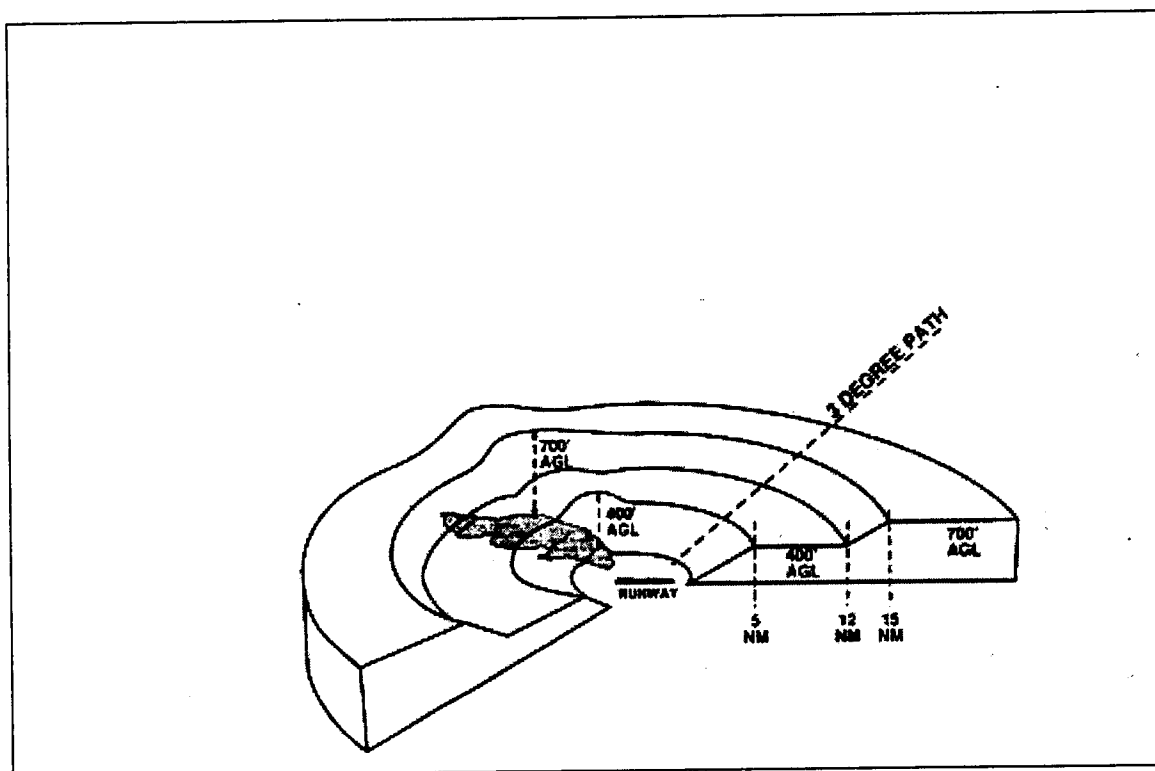


FIGURE 16 EGPWS POSITION VS AIRPORT LOCATION DATABASE

Source: *A320 Enhanced Ground Proximity Warning System*, Training Bulletin-United Airlines, 1996.

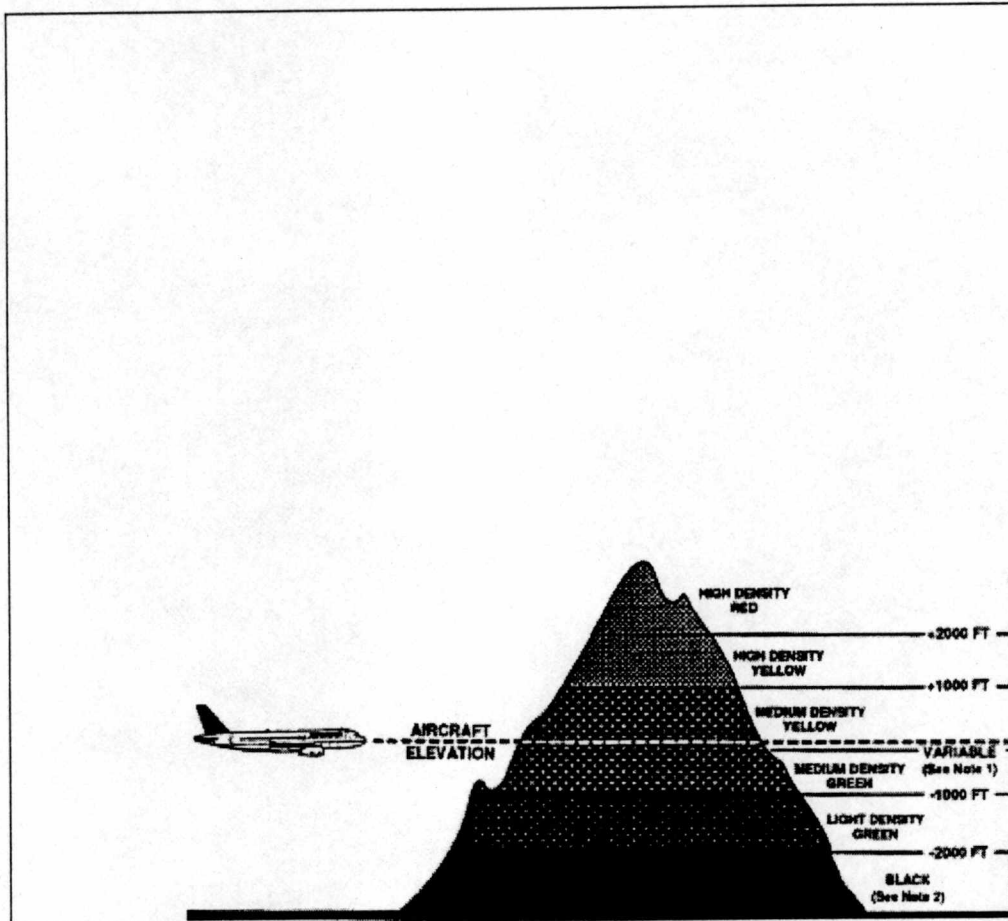


FIGURE 17 EGWS DENSITY AND COLOR PATTERNS

NOTE 1: The yellow/green boundary varies with configuration. Gear up-The boundary is 500 ft below airplane altitude, plus  $\frac{1}{2}$  sink rate greater than 1000 fpm. Gear down-The boundary is 250 ft below airplane altitude, plus  $\frac{1}{2}$  sink rate greater than 1000 fpm.

NOTE 2: Terrain is not displayed if more than 2000' below aircraft altitude and/or within 400 ft of the runway elevation of the nearest airport.

NOTE 3: Magenta is displayed for those geographical areas where terrain data is unavailable.

Source: *A320 Enhanced Ground Proximity Warning System*, Training Bulletin-United Airlines, 1996.

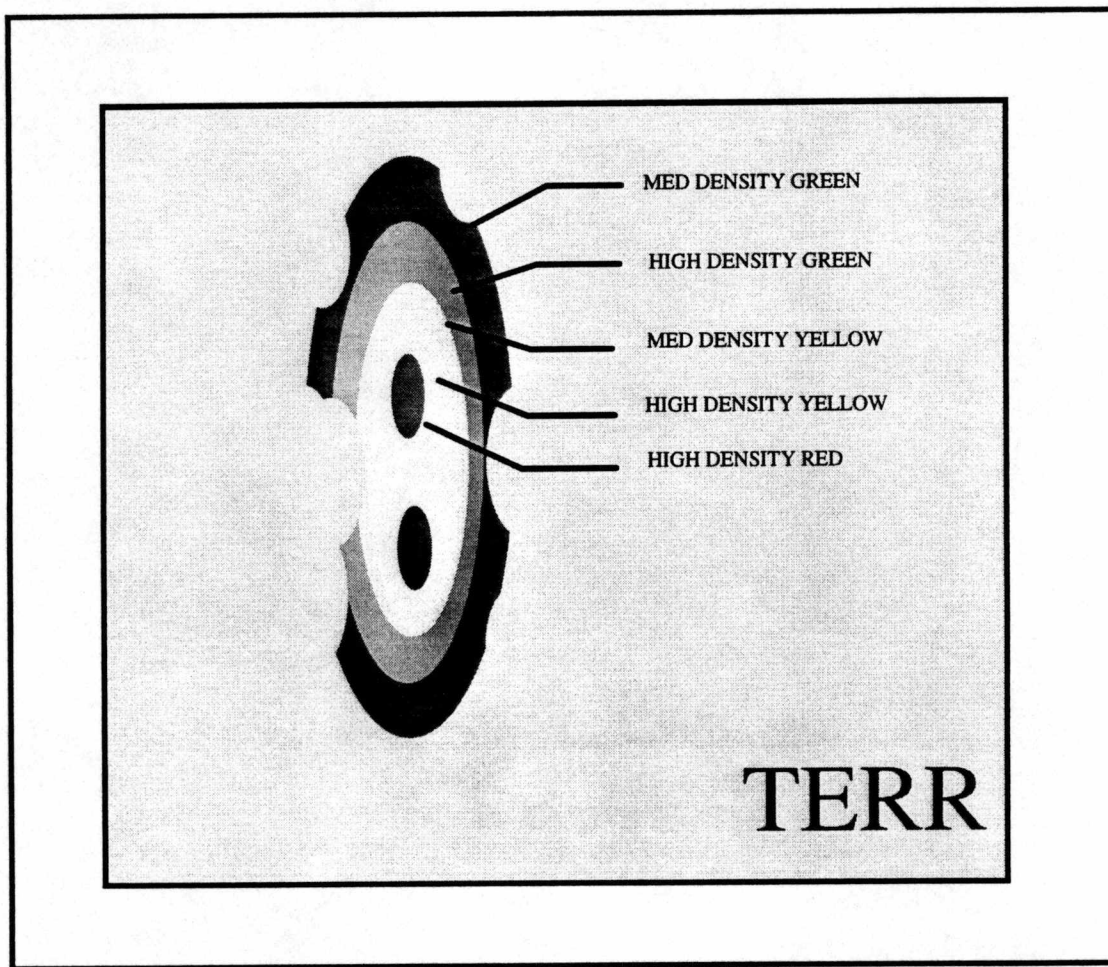


FIGURE 18 EXAMPLE EGPWS NAVIGATION DISPLAY

- is repeated every 7 seconds until clear of the threat. On the ND, all terrain at or above the threat altitude becomes a solid yellow color, except the terrain at 2000 feet and above airplane altitude, which will remain red. The TERR annunciation becomes amber. The red GPWS light on each pilot's instrument panel will illuminate.
- Warning Alerts - Approximately 20-30 seconds prior to a potential terrain conflict, a warning alert consisting of the aural "TERRAIN, TERRAIN, PULL-UP, PULL-UP, PULL-UP". . . etc., is repeated continuously until clear of the threat. On the ND, all terrain at or above the threat altitude becomes a solid red color. The TERR annunciation becomes red.

During a caution alert, pilots should verify the airplane flight path and correct it if necessary. If terrain clearance is in question, pilots should perform the terrain-avoidance maneuver recently published in the industry wide CFIT training aid, disconnect the autopilot and auto-throttle, aggressively apply maximum thrust, roll wings level, and rotate to 20 degrees pitch attitude. Retract the speed brakes, monitor radio altitude, and respect the stall warning "stickshaker" cues.<sup>1</sup>

### **SIMULATOR EVALUATION**

The Author had the privilege of flying the Airbus A-320 simulator specifically to evaluate the EGPWS. A one and a half-hour simulator mission was flown with a current A320 First Officer and a United Airlines Training Center Pilot Instructor. This was preceded by reviewing academic video tapes on the EGPWS. The mission was simulated with takeoff and landing at Reno International Airport in Nevada to provide mountainous

terrain. The EGPWS provided excellent situational awareness of surrounding terrain on the color coded navigation display. In addition, during intentional flight into terrain higher than the aircraft, the system provided timely audible and visual warnings to climb above the terrain. There were no nuisance or false alerts detected during the evaluation. EGPWS currently is posting an initial nuisance rate of less than 1 per 10,000 warning alarms.<sup>1</sup> The EGPWS is an invaluable tool for routine navigation and departure and arrival procedures.

### **LIMITATIONS**

A few limitations have already been identified using EGPWS. If a significant map shift occurs and the airplane is flying the correct navigation track using raw data, a nuisance terrain alert is possible. If a significant map shift occurs and the airplane is flying the Flight Management Guidance Computer generated track, an EGPWS terrain alert may not be generated for terrain that may actually encroach on the airplane's flight path. In this case, normal GPWS alerts are available. There are some airports that do not currently have adequate terrain data resulting in false terrain alerts if the system is not deactivated. Also, terrain clearances or descent rates during Air Traffic Control radar vectoring that are not compatible with those required by the minimum regulatory standards for EGPWS equipment may cause unwanted alerts. In aircrew systems training, instruction will need to emphasize that the background terrain display is intended to serve as a situational awareness tool only, and may not provide the accuracy and/or fidelity on which to solely base terrain avoidance maneuvering decisions. Finally,

the EGPWS terrain database, background terrain data display, and alerting algorithms do not account for man made obstructions.<sup>11</sup> EGPWS will serve the commercial airline industry well but still falls short for some military operations. The EGPWS cannot safely provide terrain clearance during low level tactical navigation. Finally, like all previous GCAS innovations, we must assume the pilot is cognizant enough to respond to the terrain alert and fly the aircraft from harms way.

## **AUTO-GROUND COLLISION AVOIDANCE SYSTEM**

The concept of an Automatic Ground Collision Avoidance System (Auto-GCAS) has been researched and simulated over the past several years. There is currently a joint program between the U.S. and Sweden capitalizing on the unique capabilities of the Advanced Fighter Technology (AFTI) F-16. The AFTI F-16 program has been actively involved in the development and testing of auto-GCAS for the last 12 years. The AFTI F-16 auto-GCAS monitors aircraft state and ground proximity for impending penetration of a pilot selectable floor altitude (distance to ground). If penetration is predicted, a "fly-up" is commanded and the auto-pilot executes and automatic recovery. The system uses both a radar altimeter and a digital terrain database to determine ground proximity. The radar altimeter is unique and provides 360 degree roll attitude coverage. The flight path of the auto-pilot's recovery maneuver is determined by the system through a reduced ordered simulation. The flight path is projected against the local digital terrain model to determine the need to initiate the auto-pilot recovery maneuver.<sup>13</sup> The fly-up maneuver requires a complicated computation with many variables and assumptions. The auto-

GCAS system computes the aircraft anticipated flight path and projects it against a terrain scan pattern. Several scan patterns are used to make the projections, and they differ for inverted and straight-and-level flight, as well as for dives. As a result, warning times vary with flight mode. Typically, the system will calculate a flight trajectory about 15 seconds in advance of the actual flight path during straight-and-level flight. One problem with today's ground avoidance systems is that the warning must come earlier than really needed to give the pilot time to react to the warning and manually execute a recovery maneuver. The automatic system lets a pilot get closer to the ground because the recovery is automatic; the system doesn't have to consider the pilot's reaction time.<sup>14</sup> A simplified auto-GCAS fly-up maneuver is presented in Figure 19. Pilot selectable options and HUD displays are similar to that already presented in the DTS section of chapter 2. Additional voice messages include preceded by the stall warning tone:<sup>15</sup>

1. "fly-up...Fly-up" when flight controls begin the auto pull-up maneuver.
2. "You've Got It" when the pilot overrides the auto pull-up maneuver or when the fly-up terminates.
3. "Power...Power" when the flight controls determine that a low airspeed condition exists.

There is clear evidence that an auto-GCAS will save lives. Since the early 1990s, the USAF has typically lost four to five aircraft a year to CFIT. The Swedish Air Force, which typically flies missions over mountainous terrain at altitudes of 15 meters (49 ft.) AGL, has an annual CFIT loss rate that's about twice that of the USAF.<sup>14</sup>

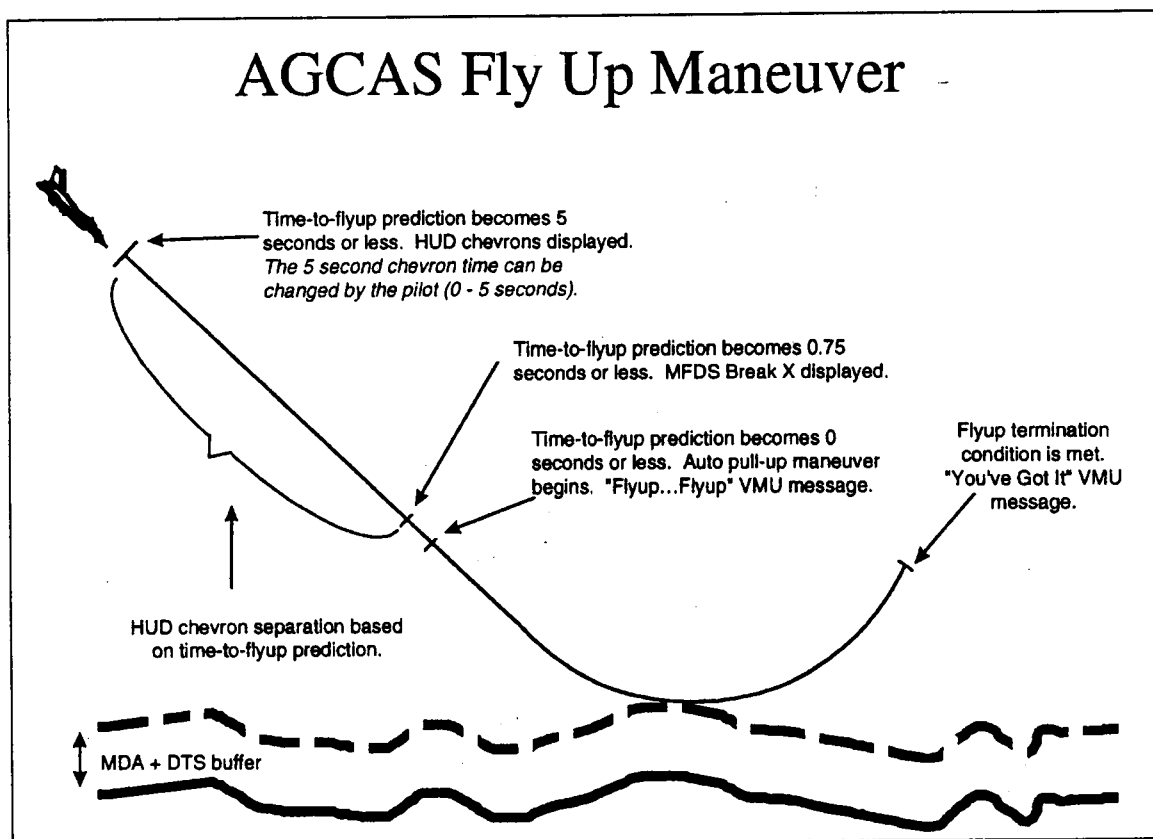


FIGURE 19 AFTI F-16 AUTO-GCAS FLY-UP MANEUVER

Source: Prosser, Kevin, *Briefing notes on AFTI/F-16 Auto Ground Collision Avoidance System*, Mar 1998.

## **LIMITATIONS**

There are many design challenges presented with auto-GCAS technology. The AFTI F-16 test team identified an issue of nuisance warnings early in flight testing. A survey within the pilot/user community showed that false warnings were the dominant flaw in existing GCAS designs. If a system issued a warning when the aircraft was not in imminent danger of impacting the ground, it was considered unwarranted or a false warning. If a system repeated warnings under these conditions it quickly became a nuisance and was either turned off or ignored by the pilot. Reliability in the timely issuance of warnings was paramount for GCAS to be acceptable. An exhaustive investigation into the significance of nuisance warnings and the difficulty in defining and presenting nuisance warning data is addressed in Reference 13. No current, auto-GCAS design incorporates maneuvering in the lateral directional axis. Recovery models presented to date assume a wings level pull or rolling pull to wing level. For example, the AFTI F-16 fly-up maneuver is a roll to wings level followed by a 5 G fly-up or, if the aircraft is inverted, a pull-up is commanded when the bank angle is less than 90 degrees. This is an area that has considerable potential in the tactical combat arena since maneuvering in the longitudinal axis can often increase aircraft exposure time to enemy defenses. Maneuvering in the lateral-directional axis could have the potential of using terrain obstacles to mask the aircraft from enemy radar. In addition, this could optimize the terrain avoidance performance of the aircraft where a vertical pull-up maneuver may not be effective to avoid terrain directly in front of the aircraft.<sup>16</sup> This Fly-up models are

also dependent on thrust assumptions. The current AFTI F-16 fly-up procedures assumes the pilot will position the throttle in accordance with flight manual recommended recovery procedures to include a 1.5 second delay. If the pilot has experienced G-induced loss of consciousness or is severely spatially disoriented, this may not be possible.

An interview with the project pilot brought out that the current fly-up model is effective with the throttle in any position other than idle. This simplified the model and inhibits fly-ups during landing but leaves the unconscious or disoriented pilot vulnerable. In addition, low airspeed, low altitude, low throttle setting scenarios are presenting a bigger challenge than high speed steep dive angle recoveries. A fly-up model that works with any throttle position or the usefulness of an auto throttle is being considered.<sup>15</sup> Many commercial and some carrier based aircraft already have an auto throttle capability.

Aircraft performance differences will present additional challenges if this technology is transferred to large transport and commercial aircraft. This will primarily be in the area of the aircraft model and in the Digital Terrain Elevation Data which will need to include man made obstructions, especially in close proximity to airports.<sup>17</sup> Also, not all aircraft have DTS capability or the computer memory available to accommodate an auto-GCAS algorithm.

Finally, the pilot-vehicle interface issues cannot be overlooked. In the past, pilot distrust of auto recovery systems has been at times a disastrous problem.<sup>15</sup> For example, the F-111 had numerous accidents attributed to the pilot disabling or improperly using the Terrain Following Radar Fail Fly-up protection. Extensive simulator and flight training

can be expected to ingrain the required trust necessary to allow an effective auto-GCAS fly-up.

## **VIRTUAL INTERFACE COCKPIT**

The GCAS technology presented so far has focused on warning or protecting the pilot from CFIT. Consideration of technology that more specifically addresses a cure for approaching the conditions leading up to CFIT is also appropriate. Promising work has been underway to employing multi-sensory, virtually augmented interfaces for future fighters. The research is taking place at the U.S. Air Force's Armstrong Laboratory at Wright-Patterson AFB, Ohio. The fundamental premise underlying this effort is that multi-sensory interfaces can optimize pilot workload, situational awareness, and overall air combat performance by taking advantage of the parallel information extraction capabilities of various sensory modalities, and by presenting critical information in an intuitive and readily comprehensible manner. To this end, The Armstrong Laboratory's Fusion Interfaces for Tactical Environments Facility is currently developing interfaces concepts that combine visual, auditory, and haptic information to enhance pilot performance.<sup>18</sup>

The increased capabilities of modern fighter aircraft can result in increase demands on pilot situational awareness, particularly in combat situations. Errors of commission and omission are both likely to occur if pilots are insufficiently aware of the various environmental and tactical factors that influence their status in a given scenario. It may be possible to design virtual interfaces that enhance the perception of spatial

orientation. For example, virtual displays could be designed to provide vertical representations of a pilot's orientation relative to the earth to guard against disorientation incidents while flying in clouds or fog. Virtual displays could also be designed which provide augmented perceptual information - that is, graphic information not directly representative of the real environment. For example, displays consisting of augmented artificial horizons could be devised that will enhance perception of orientation.<sup>18</sup> This could go beyond today's HUD presentations to incorporate a helmet or cockpit display of the horizon even when the pilot is not looking through the HUD.

One GCAS interface included during air-to-ground simulations was similar to those presented in Chapter 2 with some ingenious additions. During initial GCAS alert, all of the displays flashed red, and an auditory warning signal - a "doorbell" sound effect localized so that it appeared to emanate from the direction of the ground was presented through the headphones. Simultaneously, a large arrow was superimposed on the HUD and other cockpit multi-function displays to indicate the vertical "up" direction as an aid in recovering the aircraft to an upright attitude. The vertical "up" arrow also included a pair of brackets that moved together at rate proportional to the aircraft's closure rate with the ground. The brackets were calculated to meet at the center of the "up" arrow upon ground impact. After the initial four second "doorbell" audio warning signal was replaced with a "siren" sound effect that increased in both pitch and volume with decreasing height above the ground.<sup>18</sup> The HUD GCAS alert display is presented in Figure 20. The research at the Armstrong Laboratory has concentrated primarily on issues concerned with the development and use of virtual interfaces for fighter cockpit

applications. However, the relevance of the research program extends to commercial aircraft and all applications of virtual environment technology. Their goal has been to investigate the development of multi-sensory virtual interfaces to support performance of real-world tasks. The accomplishment of this goal will require research to be conducted on basic aspects of human perception and performance in virtual environments, as well as on applied aspects of human performance using prototype virtual environmental system. Initial findings are encouraging, and future work will be dedicated to the development of virtual interfaces for fighter cockpits to build upon the results of this preliminary work.<sup>18</sup>

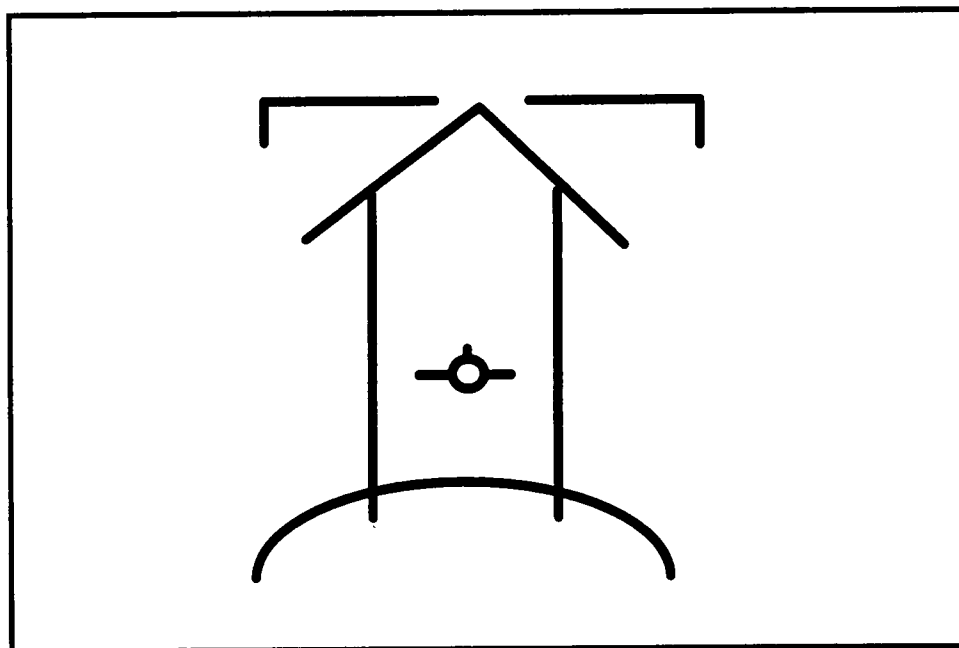


FIGURE 20 VIRTUAL INTERFACE HUD GCAS ALERT DISPLAY

Source: Hass, Michael W., Nelson, Todd W., Hettinger, Lawrence J., *Developing Virtual Interfaces for Use in Future Fighter Aircraft Cockpits*, Interim Report, Logicon Technical Services, Dayton Ohio, Jul 1994.

## **CHAPTER 4**

### **CONCLUSIONS**

The common deficiency to all current altitude and ground collision avoidance systems is the requirement for the pilot to respond to a warning cue and manually fly the aircraft out of danger. There is currently no autopilot or system fly-out capability to aid the pilot during severe spatial disorientation or in the case of G-induced loss of consciousness. Based on operational and flight test experience, in combination with the research and simulator evaluation completed for this thesis, it is the authors recommendation that future GCAS efforts include an auto fly-up capability combined with an improved situational display. There are current systems that provide fly-up protection during night or weather terrain following operations. Future aircraft design requirements should consider an auto-GCAS system similar to the one presented in this thesis as the only true measure of avoiding ground impact during low level tactical flying. Also, auto-GCAS fly-up maneuvers should utilize the lateral-directional axis for the safest terrain avoidance recovery capability and tactical terrain masking potential. The DTS situational awareness display like the EGPWS presented in this thesis provides added protection. This display provides an excellent visual tool that will prove beneficial during airport departures and approaches near high terrain. However, as pointed out in this paper, there are still design challenges to be met in both areas of technology. There is also great promise in pursuing virtual interface cockpit capability to improve the pilot's situational awareness with the intent on minimizing the need for GCAS warning or

recovery systems. Even with rapid advances in aviation technology, today's military and commercial pilots are still subject to many of the age old hazards of flight. Reports of ground collision accidents in both military and commercial aviation continue to come in almost monthly, however, human physiology and the laws of nature are not going to change. In February of 1997, the President's White House Commission on Aviation Safety challenged NASA, the FAA, and the Department of Defense to reduce the accident rate by a factor of 5 in 10 years , and by 10 in 20 years.<sup>6</sup> The technology is available to counter the tragic consequences of unintentionally flying into terrain. Aircraft system designers as well as appropriate political, military, and corporate leaders have the responsibility to use emerging technology to minimize or eliminate future CFIT accidents.

## **RECOMMENDATIONS**

Based on the author's research and flight experience with current and developing GCAS, the following specific recommendations are made:

1. Include auto-GCAS capability in current aircraft where feasible.
2. Design future aircraft with auto-GCAS capability.
3. Design auto-GCAS fly-out maneuvers to use the lateral-directional axis for the safest terrain avoidance recovery capability and tactical terrain masking potential.
4. Include DTS terrain navigation displays in aircraft for increased pilot situational awareness.
5. Include man made obstacles in DTS and institute a program for updating databases or use a forward-looking sensor to provide obstacle collision protection.
6. Continue research in virtual interface cockpit technology to improve pilot situational awareness before a GCAS warning or recovery is needed.
7. Investigate the aircrew training concerns with improperly using the EGPWS displays for navigation and for trusting auto-GCAS fly-out maneuvers.

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## REFERENCES

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## VITA

Gregory W. Carter was born in Newport News, Virginia on December 11, 1961. Raised in Kettering, Ohio, he graduated from Fairmont West High School in 1980. He attended Wright State University in Dayton, Ohio and received his bachelors degree in Systems Engineering, Mechanical Option. He was commissioned as a Regular Officer and designated a Distinguished Graduate of the Air Force Reserve Officer Training Corps at Wright State University. He was an engineering technician and then a Mechanical engineer after graduation at the Flight Dynamics Laboratory, Wright Patterson AFB, Dayton, Ohio. His experience included Terrain Following/Terrain Avoidance/Threat Avoidance TF/TA<sup>2</sup> modeling and Re-configurable Flight Control concepts for the Advanced Tactical Fighter. He then entered the United States Air Force and graduated from Undergraduate Pilot Training in October 1986 from Columbus Air Force Base, Mississippi. He remained as a T-37 instructor pilot, check pilot, and flight commander. He flew operational as a flight lead, flight commander, instructor pilot, flight examiner, and Terrain Following Radar system instructor in the F-111 E/F/G models at RAF Upper Heyford, United Kingdom and Cannon Air Force Base, New Mexico. He graduated from the U.S. Naval Test Pilot School class 110 in December 1997. He currently is an F-16 test pilot, flying safety officer, and project pilot for the Joint Stand-off Weapon (JSOW), Bomb Damage Assessment, and Block 50 Flutter Validation programs.