Benefit Analysis and Feasibility of Ground Collision Avoidance Systems on United States Air Force Aircraft

by
Jan W. Scofield

Submitted to the Alfred P. Sloan School of Management in Partial Fulfillment of the Requirements for the Degree of

MASTER OF SCIENCE in Management
at the

Massachusetts Institute of Technology
May, 1995
[June 1995]

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ABSTRACT

This thesis examines a specific type of USAF aircraft mishaps - Controlled Flight Into Terrain (CFIT) mishaps. The thesis presents data on CFIT mishaps, causes, and efforts to reduce CFIT mishaps through the development and adoption of Ground Collision Avoidance Systems (GCAS) or similar designs - Ground Proximity Warning Systems (GPWS). GPWS exist today on some USAF aircraft, but many times these systems are inadequate (as evidenced by the continued occurrence of CFIT mishaps). Both ongoing and future initiatives by the USAF to adopt and develop better GPWS/GCAS systems were studied.

An analysis was performed which studied the cost to the USAF (and the U.S. taxpayer) as a result of CFIT mishaps, and compared with an analysis of the cost to develop and implement improved GPWS/GCAS systems. The results show conclusively that installing GCAS/GPWS on a majority of USAF aircraft is cost effective. Technology exist today which could improve existing GPWS performance, and although efforts to improve GPWS are moving forward, some resistance does exist. Possible reasons for resistance of GCAS/GPWS adoption were studied and several recommendations were made on how to improve the adoption of these systems within the USAF.

Thesis Supervisor: Michael P. Rappa
Title: Associate Professor of Management

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BIOGRAPHY

The author, Mr. Jan W. Scofield has 14 years experience as a flight test engineer at the Air Force Flight Test Center (AFFTC), Edwards AFB, California including 200 hours of time in USAF fighter aircraft. He began work at the AFFTC after obtaining a Bachelor of Science in Aerospace Engineering, magna cum laude, from the University of Michigan in June 1981. He has USAF schooling and experience as a low observables (stealth)/survivability engineer and flight dynamics engineer on various aircraft including the F-16XL, the B-2 stealth bomber, and classified programs. In 1987 he received a Master of Science in Aerospace Engineering from Stanford University and returned to the AFFTC to continue work on the B-2, including first flight. In 1992, Mr. Scofield was selected to a one-year position in the USAF HQ - Pentagon, Office of Director, Air Force Test and Evaluation (AF/TE). Following the temporary assignment, he returned to the AFFTC as an Early Program Planner in the Office of the Director, AFFTC where he was then selected to the Alfred P. Sloan Fellowship Program, Massachusetts Institute of Technology in June 1994.

PREFACE

This thesis presents the results of research and analysis of data regarding USAF Ground Collision Avoidance Systems (GCAS)/Ground Proximity Warning Systems (GPWS): their cost, benefits, and feasibility. The author chose this subject as a result of the 1993 death of an extremely experienced Air Force "Viper"-pilot, who was a past work colleague and friend. He died as the result of a Controlled Flight Into Terrain (CFIT). *Even the best make mistakes.*

The author wishes to express his sincere appreciation to those in the office of USAF Flying Safety (AFSA/JAR and AFSA/SEFF) for their providing me with much of the aircraft mishap data. I would also like to thank those personnel at the AFFTC and from across the Air Force who took their time away from their jobs and family to answer my numerous and perhaps bothersome questions. Special thanks is given to Mr. Mark Skoog, a friend, colleague, and Air Force Test Manager of the Advanced Fighter Technology Integration (AFTI) F-16 at Edwards AFB, for without his valuable assistance, the data collection for this thesis would have been nearly impossible.

DISCLAIMER

Opinions or suggestions expressed in this thesis represent those of the author and not the USAF. Those persons interviewed by the author where informed that data they supplied may be used in this public releasable document/thesis.

Insert USAF release here.

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I. INTRODUCTION

This thesis presents data on a specific set of USAF aircraft mishaps - Controlled Flight Into Terrain (CFIT) mishaps and efforts to reduce these occurrences through the development and adoption of Ground Collision Avoidance Systems (GCAS) or a similar design - Ground Proximity Warning Systems (GPWS). As the data will show, a majority of these CFIT mishaps can be prevented, or the number of occurrences reduced if the mishap aircraft are equipped with a GCAS or trajectory-prediction GPWS. The central technology - Digital Terrain Elevation Data (DTED) which could be used for either of these systems exists today and has existed for nearly 10 years, yet no USAF aircraft is currently equipped with an adequate version of either GCAS/GPWS. Why? A chapter of this thesis is devoted to answering this question and what the underlying reasons are for the past resistance for adopting these life-saving and cost effective systems by collecting opinions offered by USAF pilots and USAF personnel.

Only very recently, within the past 2 to 3 years, has any serious effort been made to begin equipping certain aircraft (fighter/attack/bomber, combat type aircraft) with GCAS/predictive GPWS. These efforts however, vary with each aircraft program. Each aircraft is different, their budgets are different, and their mission requirements are different. Thus, is difficult to bring these efforts together in a focused USAF effort to equip aircraft with a common GCAS/GPWS. A GCAS/GPWS with a common "core" would have some distinct advantages over diverse efforts. By "core", I am referring to the trajectory prediction algorithm, the method by which digital terrain data is used in the algorithm, the GCAS/GPWS computer hardware, and the warning/aural symbology/tone. These advantages include reduction in acquisition and development costs due to economy of scale, reduction in maintenance and logistics costs because of system commonalty, and common system performance (for pilot proficiency and training). Although most hardware/software of a USAF-wide GCAS/GPWS system would be common across the fleet, obviously some software/hardware would have to be tailored for each type aircraft (primarily the I/O interfaces). Additionally, each aircraft program requires a modification/update to its Operational Flight Program (OFP) in order to incorporate GCAS/GPWS. OFP releases are rigidly controlled and scheduled events. They are expensive (must go through extensive development and testing) and typically occur every 2-3 years. If GCAS/GPWS is to be incorporated, it must coincide with an OFP release.

The thesis also investigates the cost to the USAF as a result of these mishaps and the cost of some representative GCAS/GPWS systems which, if feasible and adequate, could save lives. Analysis is also included on probability of CFIT mishaps broken out by type aircraft - bomber, fighter, transport, etc. As the data will show, not only are

GCAS/GPWS systems feasible, especially in fighter/attack aircraft, but they are cost effective. They will continue to become more cost effective as the cost of USAF aircraft continues to escalate and while the technology used in GCAS/GPWS components continues to become more commonplace (and thus continue to push component costs downward).

After reading the opening paragraph above, some readers may disagree with my premise that currently, no operational USAF aircraft is equipped with a GCAS. This is because the term "GCAS" is currently being used vaguely to cover a wide spectrum of ground warning/avoidance systems already in use or under development. Primitive GPWS systems which rely almost exclusively on an aircraft's radar altimeter or worse yet, rely on a crew-selected minimum Mean Sea Level (MSL) altitude "floor" as a threshold for a warning are installed on a many USAF aircraft. As evident by the CFIT mishap data presented in Chapter II and by current available technology standards, these simple GPWS systems are of little value in many instances and warrant change. As the data will show, this is especially true for fighter/attack aircraft. So what do I mean by GCAS? For the purposes of this thesis, I refer to GCAS as ground collision avoidance systems which provide automatic recovery of the aircraft in the event a collision with terrain is predicted. Predictive-GPWS is very similar to GCAS except that the aircrew is provided with only a warning of a predicted collision with terrain. In both these instances, note that the common feature is adequate prediction of a collision. Today's operational GPWS systems do not adequately predict the trajectory of the aircraft relative to the terrain in order to provide more ample warning of an imminent collision. They merely compare current altitude with a "threshold" or estimated upcoming terrain and provide a warning. Secondly, the current GPWS systems must be activated by the aircrew and thus are not always "on". GCAS/predictive GPWS should be running in "background" and be invisible to the aircrew until it is really needed (that is not to say that in some few instances, depending upon the actual GCAS design and aircraft mission, that the GCAS function may be selected to off).

As the data will show, the vast majority (72%) of the 229 mishaps classified as being caused by CFIT between 1980 and 1993 would probably have been prevented if the mishap aircraft were equipped with a GCAS and a majority (56%) would probably have prevented with a predictive GPWS. Some would argue that the loss of life alone justifies the need for GCAS/predictive GPWS. While this may be true, the money saved from using GCAS to prevent many CFIT mishaps over the cost of these systems also justifies their adoption. Not only is this true in today's dollars, but the savings becomes even greater if the continually increasing cost of aircraft is taken into account. An aircraft lost today will cost substantially more to replace in the future. Admittedly, this simple argument not strictly true. Aircraft are not replaced one for one.

Economically speaking however, opportunity costs are incurred as a result of each loss because the potential strength of the USAF is diminished.

Thesis Overview

The thesis is composed of four "main" chapters. First, the problem confronting the USAF is presented in Chapter II - The Problem. *Good* pilots are flying *good* aircraft into the ground every year at enormous human and monetary costs. Statistics which shed some light on CFIT mishap trends are presented in Chapter II along with possible explanations of the contributing factors. The majority of the data in this chapter were obtained from the USAF's Flight Safety Office at Kirtland AFB, New Mexico.

Chapter III then describes GCAS/GPWS systems and their predecessors - Terrain Following (TF) systems. Included in this system description chapter are explanations of what sensors and other equipment (DTED for example) are needed for a GCAS/GPWS to function. A brief description of the first practical GCAS onboard the USAF's experimental Advanced Fighter Technology Integration (AFTI) F-16 aircraft along with noteworthy test results and pilot comments is also provided. The chapter concludes with current and proposed initiatives for the adoption of GCAS/GPWS systems on existing and future USAF aircraft. Data were obtained from interviews with test personnel at the USAF Flight Test Center at Edwards AFB, Air Force *Flying Safety* Magazine, and a few of the comments from the pilots assigned to the AFTI F-16's 1993 Automated Recovery System Evaluation.[1]

An analysis of GCAS/GPWS cost and feasibility is presented in Chapter IV. The cost to the USAF (and U.S. taxpayer) as a result of CFIT is computed yearly for various aircraft classes (fighter/attack, bomber, transport, etc.). Using the CFIT mishap data from Chapter II, the future likelihood of CFIT mishaps involving existing, new, and future aircraft is calculated (many of the latest aircraft have not been flying long enough for their data to be used to determine a CFIT mishap rate). Next, the cost of acquiring and/or retrofitting USAF aircraft with GCAS/GPWS is computed. Data were obtained from two primary sources: the USAF Flight Safety Office and from various aircraft System Program Office (SPO) personnel (including F-16, F-15, and F-22) and other program personnel (B-2, C-17, and AFTI F-16).

Chapter V, entitled, Resistance to Adoption of GCAS, explores some possible reasons as to why no operational aircraft to date is equipped with a full GCAS/predictive GPWS. The reasons are a combination of emotional and financial factors. Distrust of the systems from pilots based upon their previous experiences, pilot and USAF headquarters uncomfortableness with the GCAS technology, and budget constraints are

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[1] Comments are from USAF Test Pilots and Lockheed-Fort Worth Division (formally General Dynamics) Test Pilots assigned to the program during the GCAS evaluation.

some of the issues explored in this chapter. Although some of these issues are intangible, they are nonetheless important to understanding the slow adoption of GCAS technology. The evidence presented is based on the experience and opinions of the author (through work as a flight test engineer) and interviews with test personnel and pilots.

II. THE PROBLEM: Controlled Flight Into Terrain (CFIT)

From 1980 through 1993, the active duty USAF (not Reserves or Nat'l Guard) has experienced 229 mishaps or incidents classified as CFIT -- Controlled Flight Into Terrain (also known as CWG -- Collision With Ground)[2]. Out of all categories of aircraft mishaps (mechanical problem, collisions with other aircraft, pilot error, etc.), CFIT is the largest single category of USAF mishaps. Roughly one out of every four mishaps involving USAF fighter/attack aircraft is a result of CFIT. Of the total 229 CFIT mishaps, 177 resulted in destroyed aircraft and/or loss of life (some are damaged). This equates to an average yearly destroyed aircraft CFIT mishap rate of 12.6 (177 destroyed CFIT aircraft divided by 14 years - 1980 to 1993). The CFIT mishap rate is 16.3 destroyed aircraft per year if all 229 CFIT mishaps are included over the same 14 year time span. Besides the loss of costly aircraft, there is also the intangible cost in terms of lives. In 1994, following CFIT mishap briefings, the then Air Force Chief of Staff, General M. McPeak dictated that GCAS/predictive GPWS are needed on USAF fighter/attack aircraft and work should begin to develop and acquire them. However, fiscal constraints mean that, though much needed, CFIT preventive systems have taken a backseat to other war fighting systems/upgrades.

Since a fixed pre-determined number and type of aircraft are bought by the DoD (as specified by the DoD budget), when an aircraft is destroyed it is not replaced directly (though it may be replaced indirectly, if an entirely new acquisition is made for that type aircraft). As a result, the potential strength of the US Armed Forces is reduced over what it may have been if the aircraft had not been lost. Calculating the actual cost is highly subjective, depending heavily upon the assumptions made, and can only be broadly estimated. More details on cost are included in the Cost/Benefit Analysis section of this paper. However, using a "ballpark" figure of $10 million per aircraft, times 177 destroyed aircraft, equates to a loss of $1.77 billion since 1980 as a result of CFIT. Similarly, at $10 million per aircraft, times 12.6 CFIT destroyed aircraft mishaps per year, equates to $126 million per year lost to CFIT. Neither of these cursory calculations adjust prices to current dollars or adequately accounts for the ever increasing cost of modern military aircraft.

What is the cost in American lives? Besides the intangibles in accounting for the loss of a life, a monetary figure can be placed on training and schooling aircrew members. The cost to the USAF as a result of CFIT is in the range of $500,000 to $1 million for an inexperienced pilot and $2 to 4 million for more senior pilots. Adding these costs to the above figures raises the total cost since 1980 to roughly $2 billion, or $150 million/year.

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[2] USAF Safety data obtained from Lt Col Krause, HQ AFSA/SEFF, Kirtland AFB, NM, *Controlled Flight Into terrain USAF History* briefing, Jan 1994

As stated above, between 1980 and 1993 there have been 229 mishaps attributable to CFIT. Of the 229:

- 172 were classified as "Class A - destroyed" (a destroyed aircraft with or without a fatality)
- 5 were "Class A" ($1M or more damage, or a fatality, or both)
- 4 were "Class B" ($200K or more or serious injury)
- 36 were "Class C" ($10K or more)
- and 12 were "HAP" or "incidents" (high accident potential, a hazard without reportable damage).

These data can be subdivided and categorized by four factors to ascertain if there are any trends, anomalies, or any further data to help describe the problem. These four factors are: The environment (day/night, weather, etc.), aircrew experience (rank and experience), the aircraft (type aircraft, F-16, F-15, etc.), and human factors (disorientation, g-induced loss of consciousness, etc.). Analyzing the data applying these factor's gives the following results:

The Environment

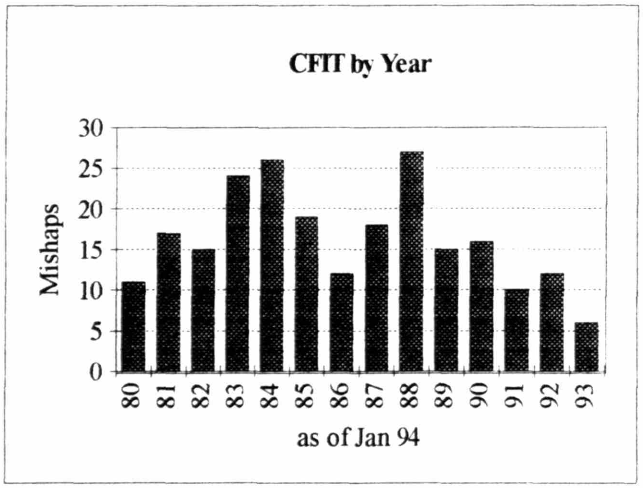

Figure II-1. Yearly CFIT

78% in day conditions
21 % at night

72% in Visual Meteorological Conditions (VMC)
25 % in Instrument Meteorological Conditions (IMC)

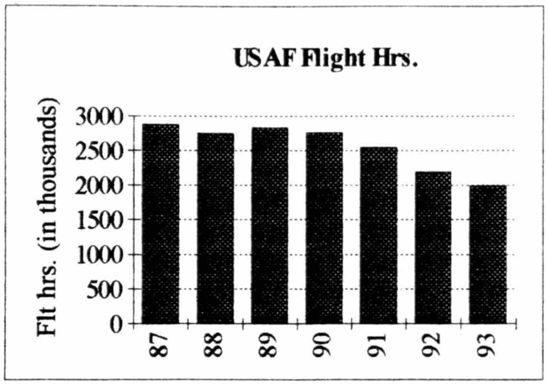

Figure II-2. Total USAF Active Duty Flight Hours[3]

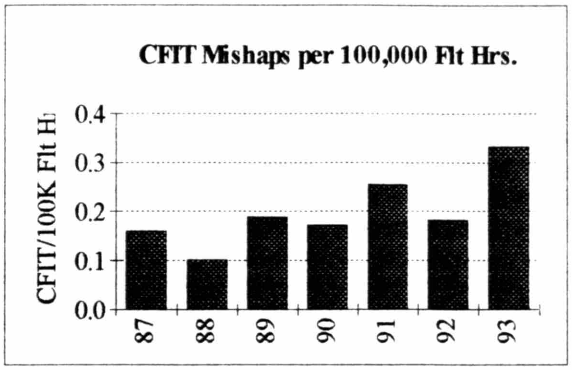

Figure II-3. CFIT Mishap Rate

Although the number of CFIT mishaps has generally decreased since 1988, the CFIT mishap rate per flight hour has generally increased. There are a number of possible explanations for this trend in the rate per flight hr. Although the data are were not available for this paper, the most likely reason is the USAF's increased reliance upon low-level flight for successful mission accomplishment. As high performance aircraft rely upon terrain masking during ingress/egress to avoid ever better air defense networks and Surface-to-Air Missiles (SAMs), the likelihood of CFIT increases because more peace-time training is performed at low level altitudes. Also, not only are more missions performed at low-level, but more maneuvering is occurring at low-level. Today's pilots are not simply performing low-level straight strafing/bombing runs, but are required to maneuver, sometimes up to 5-7 g's, while at low altitudes (tree-top level in some instances). As will be discussed on subsequent pages in more detail, factors such as cockpit complexity and distractions while flying at low-level altitudes are contributing factors to CFIT mishaps.

The data in Figure II-4 shows the overall USAF Class A mishap rate per 100,000 flight hours from 1989 through 1993. Obviously, the rate is higher than just the CFIT mishap rate shown on Figure II-3 (includes all mishaps, not just CFIT), but note that this overall mishap rate trend does not generally increase as was the case for CFIT mishaps. This supports the hypothesis that increased CFIT rate is not due to overall USAF pilot complacency or less disciplined pilots (thus increasing overall Class A mishap rate).

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[3] *Air Force* Magazine, May 1994, pg. 40

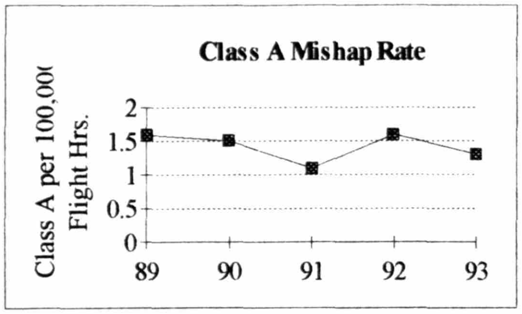

Figure II-4. Class A Mishap Rate[4]

As would be expected (see data next to Figure II-1), daytime mishaps make up the great majority of CFITs (78%). Most flying occurs during these hours. Night conditions must be respected however, because 21% occurred during darkness. The USAF is relying more heavily upon infrared and other non-visual sensors to operate at night. Thus, it would be expected that a greater number of night-time CFITs will occur as more emphasis is placed upon night operations/training. The same trend will also hold true for all-weather flying (25% CFIT were in IMC conditions).

Finally, although the emperical data are not shown in this paper, there are no true "peak or worst" months in CFIT data. The data are generally evenly distributed throughout the seasons, however December is the lowest (nearly half). The low number of mishaps in December is due to the low number of flying hours during that month, given holidays.

Experience[5]

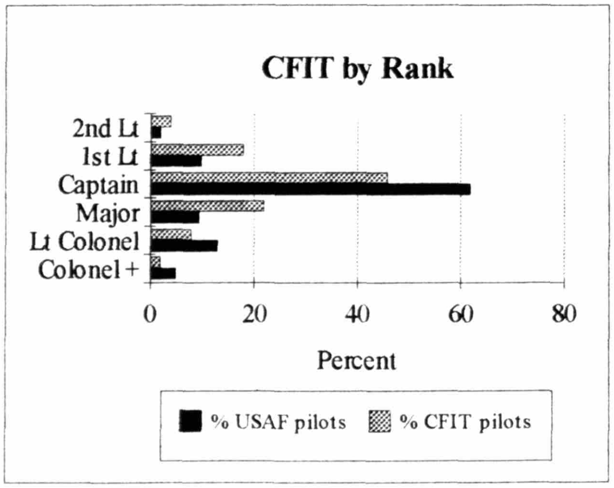

Figure II-5. CFIT by Pilot Rank

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[4] *Air Force* Magazine, May 1995, pg. 38

[5] Data obtained from HQ AFSA/SEFF, Kirtland AFB, NM, *Controlled Flight Into Terrain USAF History* briefing, Jan 1994

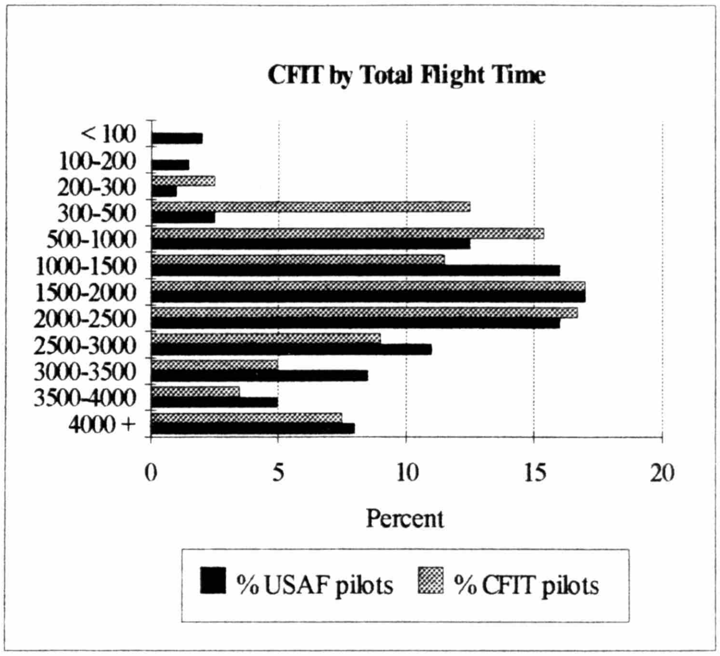

Figure II-6. CFIT by Total Flying Time

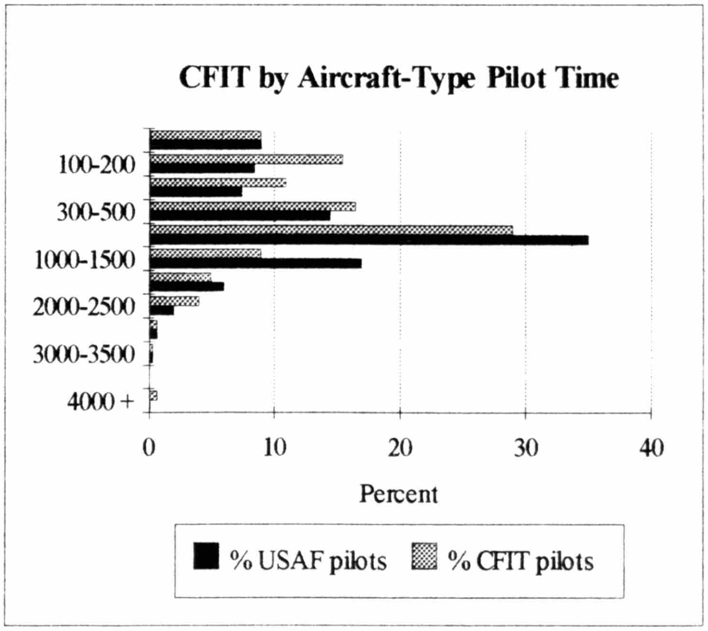

Figure II-7. CFIT by Pilot Time in Aircraft Type

Clearly, the pilot is the most important factor in CFIT mishaps. After all, they are flying the aircraft. What can be ascertained by Figure II-5? The data shows that relative to the general pilot population of the same rank, Majors have the highest CFIT mishap rate (twice as many Majors are CFIT mishaps as compared to the percentage of all pilots that are Majors). As expected, Captains have the overall highest CFIT mishap rate relative to all USAF pilots because they represent the greatest number of pilots.

As shown in Figure II-6, the most experienced crew member's total flying time at the occurrence of the CFIT mishap reflects the general population with the exception of 300-500 hours total flying time. This data suggests that inexperienced pilots with between 300 and 500 hours flying time are beginning to perform missions which make them susceptible to CFIT. This may include more low-level flying, high-g maneuvers, or night-time flying. Prior to this, aircrew are developing basic flying skills. Inexperienced pilots and other crew members may not yet have developed the situation awareness skills necessary during the taxing missions as compared with more senior pilots and crew members.

Finally, Figure II-7 shows that time-in-type CFIT mishap aircraft is a factor. Note that 40% CFIT mishaps involved a pilot with less than 500 hours in mishap aircraft type. In general, as pilots gain experience in a given type aircraft, their flying skills in that type aircraft increases. The initial rise in CFIT mishaps in a given type aircraft is most likely due to two factors. First, as pilots gain experience, they are more likely to "press the envelope" of both the aircraft and themselves, thus increasing the likelihood of a mishap. Secondly, the type missions they perform gain complexity and pilot skill requirements which then introduce a whole set of safety problems called "human factors".

The Aircraft

As expected, Figure II-8 below shows most CFIT mishaps happen to fighter-attack-reconnaissance type aircraft.

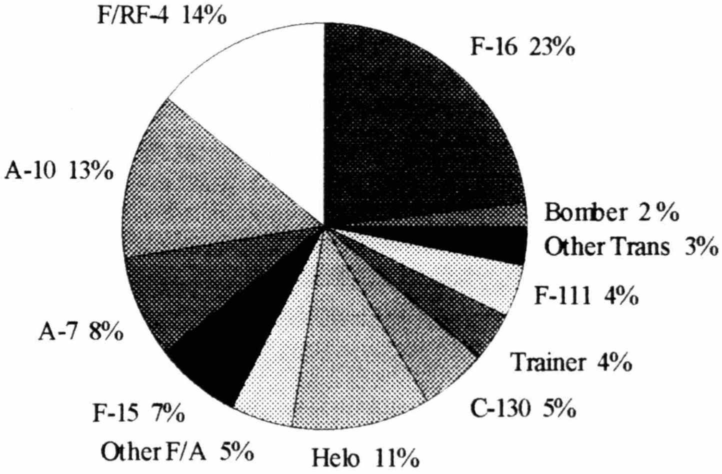

Figure II-8. CFIT by Aircraft[6]

The primary factor to why Fighter/Attack/Reconnaissance (F/A/R) account for 70% of the CFIT mishaps is that they have inherently higher-risk missions. They tend to fly low-level more often than transports/bombers and maneuver more rapidly (thus increase susceptibility to g-induced loss of consciousness, pilot disorientation, etc.). In 1993, all 6 CFIT mishaps were F-16s.

The type of maneuvers that led to ground collisions were:

- Fighter/Attack Aircraft
    - -- low level
    - -- maneuvering

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[6] HQ AFSA/SEFF, Kirtland AFB, NM, *Controlled Flight Into Terrain USAF HIstory* briefing, Jan 1994

    -- weapons delivery
    - Air Combat Training (ACT)
- Heavy/Transport Aircraft
    -- C-130 low level
    -- Others: approach/landing
- Bombers (including F-111) -- low level (especially at night)
- Helicopters
    -- low level
    -- hover or transition to landing
    -- fewer Class A's however (low speed and crashworthiness)

Human Factors

Why do *good* pilots fly *good* aircraft into the ground? All pilots and crew members are aware that the low-level flying environment is extremely dangerous and most give it the attention necessary to prevent a CFIT. However, some don't. Even the most seasoned and experienced pilots can become CFIT statistics. Note on Figures II-6 & 7, pilots with over 4000 total flight hours and with 4000 hours of time-in-type have had CFIT mishaps. As shown previously, most mishaps occur in clear weather and with good visibility. Clearly, the data demonstrate that people make mistakes even though they are fully cognizant of the demands required while flying at low-level altitudes. For years, the USAF physiological/medical experts, flight surgeons, and safety offices have stressed human factor related causes of mishaps to aircrews in order to eliminate flying mishaps of all types (not just CFITs). For example, the USAF's *Flying Safety* magazine publishes monthly flying safety articles to make crew members aware of all aspects of flying safety. The magazine can be found in crew lounges and near every Ops desk at Air Force bases across the globe. Over the years numerous articles have been written which discuss CFIT mishaps and causes. In addition, mandatory formation monthly flying safety meetings occur at Air Force bases across the globe. There are also many other forums for discussing flying safety (at the bar, other periodicals, in pre/post flight briefings, etc.). In summary, flying safety is stressed heavily throughout the career of every aviator in the Air Force and it does get the attention is deserves. So why do mishaps still occur?

Briefly, CFIT mishaps occur for the following reasons:

> Distraction - The pilot or crew members become distracted while flying at low-level, takes attention from primary task - avoiding the ground, and collides with it.
> G-Induced Loss of Consciousness (GLOC) - The g-onset rate of modern military aircraft in some cases may exceed the crew member's ability to "stay

ahead" of the g's (which pulls blood from the head) and may subsequently result in loss of consciousness. Note: GLOC at high altitude (>30,000 ft.) may still result in CFIT if pilot does not regain consciousness in time in high rate descent.

Spatial Disorientation - This is most likely to occur in low visibility conditions and/or at night. The pilot becomes disoriented, losses track of where exactly the ground is, and collides with it.

Visual Illusions caused by low-level flight/turning (not hallucination) - Although closely related to disorientation, this is the false perception of the flying situation such as a unnoticed descent during a high-g low-altitude turn.

Distraction

The foremost task for an aviator at low altitude who is not landing is: *avoid the ground* - it usually has a probability of kill (P_k) equal to 1.0. *All* other tasks are secondary. Too frequently, the pilot becomes distracted by something, diverting attention away from avoiding the ground, and thereby becomes another statistic. The distraction may be in the cockpit: a warning light, an instrument, a checklist, etc. or the distraction may be something outside the cockpit: the foe, a landmark, or in some cases, pilots have become so fixated on a ground target that they mentally block out everything else.

Both internal and external distractions are possible, but today's (and tomorrow's) modern, high-technology aircraft compound the susceptibility to distractions. Today's technology and mission demands have made cockpits one of the most complex and demanding work environments in the world. As will be discussed in further detail in the GCAS Description section, in some cases just providing a warning (visual and/or aural) of an imminent collision with ground may not guarantee that the pilot will acknowledge it and take action to avoid the mishap. He/she may be so task saturated (bombing the target, timing a navigation waypoint right on the mark, etc.) that he/she will subconsciously block out the warning because it is a distraction to the perceived primary task (remember the primary task at low-level is to avoid colliding with the ground). There are documented cases from Vietnam and the Gulf War of aircrew not acting on warnings. During Vietnam, some aircrew turned their Radar Warning (RAW) systems off so as to not distract them because they were constantly sounding alarms. Also, nuisance (false or undesirable) warnings compound the distraction problem. This is the classic "Cry Wolf" problem. If a warning goes off falsely 10 times, if on the 11th time the warning is accurate/true, the crew member may be likely to disregard the warning (if he/she hasn't already turned off the system). The warning does not even have to be false to be a nuisance. For instance; if a low altitude warning is set for 500 ft. and portions of a mission (low altitude bombing for example) involve flying near the ground, the pilot may deviate below 500 ft more than once, thus engaging the warning. The deviations may or may not be intentional. Depending upon the mission task and the pilot, this warning may be classified as a nuisance because it is an undesirable distraction.

In one rare instance, a pilot did not necessarily become distracted before becoming a CFIT mishap, but instead, did not realize the enormous ground closer rate because he was at a high enough altitude to not sense a "ground rush" which usually accompanies flight close to the ground. The seasoned pilot became a fatal, CFIT mishap while performing a high speed maneuver at high altitude (not due to GLOC). The mishap pilot initiated a 90 degree, afterburner dive in an effort to gain position on a low flying adversary. At the recovery initiation altitude the pilot did not realize that he was in a "fatal box" (out of ejection seat envelope due to speed and sink rate and too low to pull out of the dive before impact) and pulled to 6-7 g's. As the aircraft continued to descend rapidly and pull out of the dive, he realized the situation and pulled to nine g's, pulled the throttles back to idle, and deployed speedbrakes. A "by the book" recovery, but one which struck the ground 10 degrees nose low and out of the ejection seat envelope.

G-Induced Loss of Consciousness (GLOC)

GLOC is a known or suspected factor in 20 (9%) of the 229 CFIT mishaps between 1980 and 1993. Beginning primarily with the F-16 and F-15 aircraft, the susceptibility to GLOC increased substantially as compared to the F-4 or A-7 aircraft. The reason is two-fold. First, modern fighters g-onset rate capability can be as high as 5-7 g's per second. Future fighters such as the F-22 (due for first flight in 1997) will have even higher rates (exact numbers are classified). Secondly, today's modern fighter aircraft can sustain high g's (up to 9) for long periods of time or indefinitely. In many instances, the aircraft's structural and aerodynamic capability can exceed that of the pilot. A pilot weighing 180 lbs under normal conditions, weighs 80% of a ton (1620 lbs.) while pulling 9 g's. Not only is the pilot trying to stay alert and not blackout, but must also continue other tasks - looking at instruments, flying the aircraft, looking for/avoiding enemy, listening to radio calls, and avoiding the ground if flying at low altitude.

With a g-onset rates and g-sustainment, a pilot can literally knock him/herself out by pulling aft on the stick rapidly and/or holding it. If the pilot is not adequately prepared for the maneuver by performing the L-1 or M-1 straining exercise prior to and during the pull, the g-suit inflation rate will probably not be enough to prevent blackout or possibly LOC (modern g-suits provide an extra 3-4 g capability over effective straining maneuvers). The L-1/M-1 straining maneuvers are physical actions performed by the pilot to help tolerate g's by raising the pilot's blood pressure high enough to keep the blood from being pulled from the head. The action involves tensing the muscles in the body, holding breath for roughly 5 seconds, followed by a quick exhale/inhale, and repeating throughout the g's. Correctly performing a maximum straining exercise while under 1-g conditions is not recommended (ruptures capillaries in the brain, eyes, etc.), but is quite effective in keeping blood in the brain under multiple g-forces. The new flight tested *Combat Edge* g-suit system currently being adopted by the USAF, is an improvement over current standard issue g-suits and does have higher inflation rates. It also covers more of the body, including a torso jacket and a positive-pressure breathing system. Though *Combat Edge* will still not replace effective straining maneuvers, it will make g's easier for the pilot, reducing fatigue, and thereby reducing the number of GLOC incidents. Current g-suits designs have not changed much since their introduction and only constrict on the legs and waist.

GLOC certainly can be fatal in low-level flying. However, GLOC can also be fatal at higher altitudes. If a pilot has an LOC occurrence at high altitude and the aircraft then descends towards the earth, unless action is taken to stop the descent, a CFIT will occur. The USAF has conducted extensive studies in centrifuges regarding GLOC. Typically, unconsciousness may last between 10-30 seconds (once the high g's are relaxed), followed by consciousness, but the crew member may be in a state of near total disorientation for another 5-20 seconds. Initially, during this time, the crew member doesn't know where he/she is, and may not even realize they are flying. At the end of the episode, when they realize they are flying in a complex military aircraft, yet another 5-20 seconds are needed to read the aircraft flight instruments and ascertain the spatial orientation (if the horizon is not visible), altitude, airspeed, etc. and take corrective action. A typical GLOC episode from LOC to Time-to-Useful Consciousness lasts anywhere from 30 - 90 seconds. As a result, GLOC at 30,000 feet could be fatal if the aircraft is in a high rate of descent (20,000 ft/min). The USAF has released an F-16B (two-seat F-16) cockpit video and which has been shown on network television of a student's GLOC episode (luckily the instructor pilot in the rear seat took command of the aircraft and recovered from the maneuver). The video begins with the student maneuvering the aircraft during a dog-fight training exercise at 20K feet. The student performs a split-S aerial maneuver (rolls inverted and pulls through a descending half-loop to the opposite horizon, thus reversing heading) and GLOCs. The instructor can be heard in the back seat telling the student to arrest the high descent rate. Fortunately, the instructor recovers the aircraft near 5000 feet AGL (Above ground level). The entire episode takes roughly 30 seconds and had the student been alone, he would have been another CFIT fatality.

Spatial Disorientation (SDO)

SDO and the next category, visual illusion are known or suspected factor in 44 (19%) of the 229 mishaps between 1980 and 1993. SDO is most likely to occur in low visibility conditions and/or at night. Humans rely a great deal on sight to maintain balance and orientation (hence the enormous popularity of IMAX movie theaters which rely only on sight to make people dizzy). Since flying induces g's on the body and the inner ear, if the visual stimulus is removed or is not the primary sensor, the risk for disorientation increases. Included in disorientation, is a condition at night in which ground lights may appear to be stars (and visa-versa). A large number of SDO collisions with ground occurred during approach/landing at night or in the weather. As with other human factor safety problems, USAF has provided aviators with much information in *Flying Safety* magazine, simulator rides, briefings, etc. to help make them aware of the symptoms and causes of SDO. Military pilots are taught from the beginning of pilot training to cross-check instruments. If aviators know what to expect or what to do in the event they become disoriented, then the occurrences of SDO mishaps should decrease (everything else being equal).

F-117 Stealth Fighter missions occur predominantly at night and as a result, the aircraft has been equipped with a Pilot Activated Recovery System (PARS) which rolls the aircraft upright and pulls away from the terrain if the pilot becomes disoriented and activates the system. As will be described in more detail in the GCAS/GPWS Description chapter of this paper, this is the only auto-recovery system installed onboard USAF aircraft.

Many civilian pilots who are only VMC cleared (not instrument rated) discovered the hard way about spatial disorientation. They fly into weather, then begin a gentle turn (usually to begin setup to an approach) and hold the turn. Next they do something fatal - trust their senses (seat of the pants, i.e., g-forces) instead of the aircraft instruments which are telling them the correct attitude of the aircraft. When they roll out of the turn, their inner ear and balance has readjusted and fooled them into thinking they are banking the opposite direction, so they roll to what they sense as wings-level which is really a turn back in the original direction. Thus, they continue to turn, loose airspeed, tighten the turn to maintain what they feel as 1-g, and spiral to stall or ground collision. This is commonly referred to the "dead-man spiral". This problem is exacerbated in high performance aircraft where the g capability, descent rates, and airspeeds are much greater.

Visual Illusions caused by low-level flight/turning[7]

Visual illusions caused by low-level flight in CFIT mishaps are a subset of spatial disorientation, but are unique to low-level flight and warrant further discussion. Although it is estimated less than 1 percent of total fighter/attack flying time is spent performing turns in the low-level environment, 6 percent of Class A mishaps (10 mishaps) occurred in that regime. Why is low-level turning so dangerous; two factors

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[7] USAF *Flying Safety* Magazine, Low-Level Turning and Looking Mishaps, Oct 1990, pg 3.

- one based on physics/aerodynamics, and the other based on the fooling of our orientation senses into not recognizing overbanked turns and descent rates.

First the physics and aerodynamics of low-level turns. In straight and level flight at 500 feet at 500 knots (392 ft/sec), if a 1-degree unrecognized descent develops, the time to until impact is 35 seconds. In a 4-g turn at 500 feet, if a 10 degree overbank develops, the time to impact is only 5.8 seconds. This leaves very little time for the pilot to look away from the nose (to prevent a nose slice and subsequent ground collision) for an adversary or landmark. Why the overbank in the first place? That leads to the second factor in low-level turning mishaps - g-excess illusion.

The *g-excess illusion/effect* is an exaggerated sensation of body tilt caused by a greater than 1-g force on the otolith organs of the inner ear (organs which detect direction and intensity of gravity and g-forces). If the head is tilted back in a 1-g environment, say 30 degrees, your otolith organ create a 30 degree tilt sensation. If you now tilt your head back in a 2-g environment, your otolith organs send a larger signal to the brain (the tilt plus extra g), resulting in a perception of a tilt greater than 30 degrees. What does that mean to a pilot turning in low-level flight? In the absence of overriding visual cues, a pilot looking to the left horizon in a tight left bank (causing him to tilt his head back) may make dangerous control errors to falsely correct for the g-excess illusion. Laboratory studies reveal that 2-g forces can create perceptual errors on the order of 10 to 20 degrees bank angle.

The g-excess illusion and the unforgiving aerodynamics of low-level turning conspire to make low-level flight and looking anywhere except out the nose a potentially fatal act. If pilots are aware of these phenomena and expect a false sensation when looking at an adversary or into the cockpit during turning flight, hopefully they will look away from the nose briefly and only after ensuring they are not in a descent.

Lower Left Corner of Flight Envelope Problem.[8]

A potential cause of CFIT mishaps in the future which warrants some discussion concerns low speed/high angle-of-attack (AOA) maneuvering. As more advancement is made in maneuvering at low speed while at low altitude (the lower left corner of an altitude versus airspeed plot), such as being tested on experimental aircraft at Edwards AFB (X-31, F-16 MATV, and the USAF's newest fighter - the F-22), a new problem with CFIT emerges. In this case the aircraft maneuvers aggressively enough to bleed airspeed and transitions to a high AOA state, yet remains maneuverable (though somewhat limited) about it's roll, pitch, and yaw axes. The problem is, the aircraft's energy/speed may too low to maintain altitude if still maneuvering or is unable to avoid

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[8] Discussion with Air Force flight test engineer assigned to F-22 program.

a collision with terrain. High AOA induces high drag and thus causes difficulty in accelerating while trying to regain energy. To recover from this condition, either the nose must be pointed down to gain energy and AOA reduced so as to maneuver, or the engine(s) must supply enough propulsion to quickly gain energy to maneuver/recover and avoid the adversary. In either event, the aircraft is more susceptable to CFIT and thus, a GPWS or GCAS would be useful. The computations required for a GCAS or predictive GPWS system in this lower left corner problem must account for the low energy state of the aircraft in their terrain collision warning/ auto-recovery maneuver algorithms. This is not an easy problem to tackle.

Summary of the Problem

Conclusions:

- 229 CFITs between 1980 and 1993
- Low experience in mishap-type aircraft a factor
- Fighter/Attack/Recce aircraft at highest risk (majority are F-16)
- Transport/heavy at risk during approach/landing (esp. at night)
- Although number of CFIT mishaps on slight decline, the rate per flight hour is on the increase
- As cost of aircraft rise, CFIT cost will most likely rise (unless CFIT rate falls dramatically)

Flying can be dangerous. Low-altitude flying is particularly dangerous. The military has a slogan, "Train to Fight and Fight like you Train". Since the USAF tactics involve the use of the terrain to hide and evade the enemy, low-altitude flight during peace time is a necessity. Human error while flying high performance aircraft will always be a factor. Mistakes made while flying, especially at low-altitude, can be fatal and costly. One facet in trying to reduce (and eliminate) mishaps, including CFIT mishaps is educating aircrews to the dangers, symptoms, and physics of low-level flying. I discussed a few of the methods the USAF uses in educating their aircrews regarding flying safety: monthly articles in *Flying Safety*, periodic articles in *Air Force Magazine*, *Aviation Week*, and others. In addition there are mandatory monthly flying safety meetings for aviators, pre- and post-flight briefing for every sortie, and one the best old-fashioned methods: word-of-mouth.

Simply educating aircrews is not enough as demonstrated by the continuing occurrence of CFIT mishaps. Currently, F-16 and F-15 fighter aircraft have very simple, primitive Ground Proximity Warning Systems (GPWS). However, these systems need improvement (there is work under way to accomplish this as will be discussed in the next section). The KC-135 and KC-10 tankers are also equipped with a GPWS system.

All these and other systems will be discussed in the next section, Ground Collision Avoidance Systems (GCAS): Descriptions and Current Solutions.

How many of the 229 CFIT mishaps between 1980 and 1993 were preventable if the aircraft were equipped with either a GPWS (warning only GCAS) or a GCAS (active, take control) type system? The USAF Safety office, HQ AFSA/SEFF, Kirtland AFB, NM has done such an estimate. They estimate that if the mishap aircraft were equipped with:

- Auto recovery GCAS[9]
    - -- 165 probably preventable (72% of 229)
    - -- 3 possibly prevented
    - -- 53 probably not prevented
- Warning only GCAS
    - -- 129 probably prevented (56% of 229)
    - -- 21 possibly prevented
    - -- 71 probably not prevented
- 6 unknown

In addition, the USAF requested the Advanced Fighter Technology Integration (AFTI) F-16 aircraft located at Edwards AFB to re-fly the mishap profiles of all 1993's six F-16 CFIT mishaps. As will be discussed in further detail in the next section, the AFTI F-16 aircraft is equipped with a state-of-the-art active (auto recovery) GCAS. In all six mishaps, the AFTI F-16 successfully recovered the aircraft demonstrating that if the mishap aircraft had been equipped with GCAS, the mishaps could have been prevented[10]. At a conservative rough estimate of $15 million per F-16, that could have been a savings of $90 million.

As the cost of new aircraft such as the F-22, F-15E, B-2, and C-17 rise, the cost of CFIT mishaps will rise. For example, the estimated cost of an F-22 is near $80 million and an F-15E near $30 to 40 million. The USAF simply cannot afford to loose aircraft of this price if such CFIT mishaps are preventable by readily available technology. The relative cost is even greater when you take into account the shrinking number of aircraft built for the future protection of our country. The next section describes what can be done to reduce the number of CFIT mishaps in the future.

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[9] GCAS data assumes: predictive algorithm, not attitude limited, and 360 degree roll coverage. The term "Preventable" assumes hypothetically that an adequate system was installed onboard the mishap aircraft.

[10] Interview with Mark S. Skoog, AFTI F-16 Flight Test Program Manager, Edwards AFB, CA., Jan 1995.

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III. GROUND COLLISION AVOIDANCE SYSTEMS (GCAS), GROUND PROXIMITY WARNING SYSTEMS (GPWS): Descriptions and Current Solutions.

As the title of this section implies, onboard systems which aid the pilot in avoiding a collision with the ground are divided into two categories. Commonly these two terms, GCAS and GPWS, are used interchangeably. For the purposes of this paper, I refer to GCAS systems as those that have automatic recovery (independent of aircrew) capability, and GPWS as those that provide warning to the aircrew but do not automatically recover the aircraft. As will be discussed, each have their advantages and disadvantages. Also included in this section is a discussion of GCAS/GPWS systems employed today in the USAF and initiatives to modify existing aircraft, including F-16s and F-15s, with GCAS/GPWS systems.

Besides categorizing ground avoidance/warning systems into GCAS or GPWS, each type may rely upon sensors (active/transmitting, such as radar or passive/receive only, such as infrared) and/or each type may rely upon stored data (in the form of a map in avionics memory or infrared sensor) to help avoid collisions with the ground/obstacles. Each of these also have their advantages and disadvantages which I will discuss.

How do GCAS and GPWS systems work? What are their sensor and data requirements? Before addressing the details of, and differences between, GCAS and GPWS systems, I will discuss one of the most critical parts of these systems because it is common to both types - the detection or knowledge of where the terrain is using sensors and/or digitally stored terrain data.

Sensors (active and passive)[11]

The most common and versatile sensors utilized on today's aircraft is radar (RAdio Detection And Ranging). In most instances, it can look through weather, function in day or night, and has long range. All of which are necessary requirements for most USAF missions, including low-altitude missions. With the exception of the F-117 Stealth Fighter and training aircraft (T-38, A-37, etc.), nearly all USAF aircraft are equipped with radar. As will be discussed later however, only a few have the capability to look-down at the terrain for obstacle avoidance purposes because these type radar are very expensive. More importantly, radar must be transmitted as well as received. In today's USAF, stealth and surprise is a very important aspect of mission success. Transmitting a radar signal may broadcast your location to the enemy, which is counter to stealth tactics. Also, the radar signal may be jammed. Secondly,

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[11] Details about the various sensor and navigational systems utilized onboard many aircraft are outside the scope of this paper and may be found in textbooks and other academia articles. However for the purposes of this paper, some limited discussion is included.

transmitting a radar signal strong enough to detect small Radar Cross Section (RCS) targets at tens or near a hundred miles requires significant power (especially when the signal is pulsed as most pulsed-Doppler radar are on modern military aircraft). Power is something which is scarce and valuable on aircraft.

Basically, two types of radar may be used for terrain detection on USAF aircraft. The first type is the aircraft's main/weapon radar usually located in, or near, the nose of the aircraft (the B-2 has two main/weapons radar located on either side of the "chin" of the aircraft), or carried in the nose of an external carriage pod. Primary/weapons radar are steerable (either mechanically or electronically on modern radar) and have very narrow beamwidths (thus have high resolution, are more power efficient than wider beam width radar, and are mode agile). The second type radar used for GPWS and during approach/landings is a special single-function radar - the radar altimeter. This radar is used for one purpose, as the name implies, to precisely determine the height above the ground. The first type, the main/weapon radar performs most of the primary mission tasks such as airborne target detection/ranging/tracking, ground mapping (using Synthetic Aperture Radar - SAR techniques if the radar is capable), or weather mapping. Most radar utilized on USAF aircraft have an air-to-air function or look-down to the earth to detect/track targets, but they cannot use this radar to navigate at low altitude above the terrain. The F-16C/D, F-15C/D, and other USAF standard fighters involved with the vast majority of CFIT mishaps (see The Problem section of this paper) do not have radar which can be used for low altitude terrain-following missions or for GCAS/GPWS purposes (unless in a special bombing mode). To perform low-altitude terrain following/avoidance missions, aircraft must have radar built for that purpose. Some models of the F-111 and B-52, and all B-1 and B-2 can perform this low altitude mission. The Low Altitude Navigation/Target Infrared for Night (LANTIRN) models of the F-16 and the F-15E Strike Eagle rely upon Infrared-aided systems as well as a special look-into-terrain capable radar in the LANTIRN pod to perform these unique missions manually at night or in low-visibility weather conditions.

Unlike look-down primary/weapons radar, radar altimeters are standard equipment on nearly all USAF aircraft. They can be used to assist in the GCAS/GPWS function. Radar altimeters require only a small antenna (a few inches diameter, but therefore has a wide beam width), are mounted pointing downward, and are usually not steerable. Designs are underway to mold radar radomes, including radar altimeters, into the aircraft structures such as wings and steer them electronically. This would give much more flexibility to aerodynamicists as well as radar/weapons systems engineers than exists today when designing future aircraft.

Another category of sensors are those that are passive (do not transmit). Infrared (IR) sensors fall into this category. The usefulness of these sensors is there application for stealth tactics. A purely passive sensor onboard an aircraft does not emit energy, thus does not give away position to the adversary. Secondly, because these sensors do not transmit, their power requirements (which is valuable and scarce on aircraft, especially fighters) are less than those that do transmit. Forward Looking Infrared (FLIR) sensors can be used in day, night, or in some instances, weather. They receive energy in the IR spectrum and create a "scene" much like a visual scene and display it to the aircrew. The range of an IR sensor however, is much less than airborne radar due to atmospheric attenuation, but adequate for piloting. FLIR is utilized on the F-117, Low Altitude Navigation/Target Infrared for Night (LANTIRN) equipped F-16s, and F-15E Strike Eagles for night & weather navigation, and targeting purposes. The scene generated from FLIR is very near picture quality and technology advances will continue to improve its uses. Other aircraft such as the A-10 and PAVE equipped F-111 use IR sensors for targeting only.

Though not used directly to sense terrain or obstacles, but very important for related reasons to be discussed later, is Global Positioning System (GPS). GPS is currently installed, or planned to be installed, on nearly all USAF combat aircraft. A GPS receiver receives signals transmitted from a constellation of GPS-satellites in orbit above the earth. From these signals, position and velocity information can be calculated and used for navigational purposes in day, night, or weather. For obvious reasons, knowing your present position (latitude, longitude, and certainly elevation) is extremely important when using this navigational data to avoid the terrain. The accuracy of standard GPS systems currently installed on most USAF aircraft is on the order of 100 feet spherical. However, with differential GPS, this position accuracy can be improved to roughly 10 feet spherical[12]. The USAF is currently in the process of approving Differential-GPS for non-precision approaches.

The requirements for military aircraft navigational accuracy are more stringent than standard GPS alone can provide, therefore, GPS can be coupled (through the Kalman Filtering in the navigation solution) with an aircraft's Inertial Navigation System (INS) to update and correct the INS's inherent drift property. Without GPS, aircraft INS updates can be performed using the aircraft's terrain-looking radar, FLIR, astro(star)-tracker (which do operate in day, but not through clouds), or laser. As stated previously, only some USAF aircraft are equipped with any one of these systems. Without INS update capability, horizontal drift errors of hundreds or thousands of feet can build-up with time during missions. Baro (air data derived altitude) damping is utilized in the vertical axis to contain INS derived altitude errors to as low as possible

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[12] Data obtained from USAF Range Control Officer at Edwards AFB, CA. There are plans to install Differential GPS on many USAF aircraft in the future, but is limited by fiscal and requirement constraints.

(tens of feet or less). Before radar/FLIR/astro/lasers were utilized, INS updates were performed manually by the aircrew. Along the planned flight path, known fixed ground targets' (known man-made objects are usually the easiest to detect) latitudes/longitudes/elevations are loaded into INS memory and when the aircraft overflies these points, the aircraft's radar/FLIR/laser searches and identifies the ground targets along the route. Next, INS-derived position is compared to a given target's known position and the INS is then updated from the ground target data stored in memory. How often these updates are performed is dependent upon the INS accuracy requirement, but generally occur every 20-60 minutes and achieve on the order of 100 ft accuracy. As will be discussed below, this same update procedure or an update using the radar altimeter can be performed to update relative position on a digital terrain map, but does not function so well over rough terrain.

Digital Terrain Elevation Data (DTED)

The last tool I will discuss used for determining/detecting terrain position is stored terrain/map data. Recent advancements in computers and optical data storage have enabled terrain data to be loaded (via CD-ROM) onboard aircraft before and during flight and used in real-time to navigate. For this digital data to be loaded/accessed, the aircraft must be equipped with a digital data reader of some sort. As will be described in the GPWS and GCAS Initiatives portion near the end of this chapter, some aircraft already have digital Data Transfer Cartridges (termed DTC by the Air Force), but they must be upgraded to handle the much larger DTED data set. A necessity of using DTED data to navigate/avoid terrain is the aircraft's stored-map derived position must be compared to the aircraft's true position. As stated previously, the aircraft's true position usually comes from an updated INS position or possibly GPS if so equipped. If the aircraft does not have radar/FLIR update capability (as most don't), the radar altimeter may be used to improve position error between where the aircraft is relative to the digital map and the aircraft's true position by comparing the difference between the radar altitude and the INS computed altitude to the digital terrain. This is not nearly as accurate as a radar/FLIR target update however, especially over rough/mountainous terrain because it is difficult to correlate highly variable DTED terrain elevation data with rapidly changing radar altitude to ascertain horizontal position. The Navy's "Tomahawk" and USAF's Air-Launched Cruise Missiles (ALCMs) used successfully in Operation Desert Storm relied upon stored terrain/map data (INS updated by radar) to navigate hundreds of miles to their targets.

These digital terrain maps can be extremely accurate, include man-made obstacles (assuming you know they are there) as well as natural obstacles (including trees), and can cover an area as large as 40,000 sq. miles. The size and accuracy of the data base loaded onboard depends upon the accuracy and size of the map required as well as the computer capacity onboard the aircraft. The raw data for these digital maps are supplied by the DoD's Defense Mapping Agency (DMA) and has accuracy's on the order of tens of meters[13]. Within the US, DMA data may be surveyed to very fine detail if needed. The exact methodology used to create maps for foreign territory is classified.

The DMA-derived Digital Terrain Elevation Data (DTED) Level I digital database consists of files containing cells of a predetermined size (for instance, 1 degree by 1 degree widths). Each cell has its horizontal and vertical errors specified. The errors are a function of the sources used to obtain the data and the techniques used to process the data, as well as the earth model (WGS 84) used for reference. To convert this elliptical earth map data onto a 3-dimensional grid containing elevation data and meet onboard memory and computational speed requirements, this DTED data must be converted to a more course data set. Obviously, the more powerful the onboard processing , the finer the grid (for a given size map coverage area). To convert the DTED data to say, a 100 meter equidistant grid, a Lambert Conformal Conic Transformation[14] is performed. A 2-D grid results with a grid-spacing of 100 meters and a "post" at the center of each grid which represents the highest elevation of that specific 100-by-100 meter grid-box. This 100-meter spacing post-network of the entire map area is then hosted on a large capacity storage medium (optical). How this data is then used for terrain avoidance will be explained in the GCAS and GPWS Specifics section.

Terrain Following/Terrain Avoidance (TF/TA) : GCAS and GPWS Predecessor

How do GCAS and GPWS systems work? Probably the best way to begin is to explain how their predecessor and closely related systems, TF/TA systems, work. TF/TA is performed by following a desired azimuth route to a destination at 100-200 feet above the terrain. The pilot (or autopilot) flies the aircraft route making bank angle corrections to keep the aircraft on the intended route and simultaneously, either the pilot or auto TF/TA system strives to keep the aircraft at the desired altitude above the terrain using pitch axis controls. TF/TA systems were installed on a few aircraft in the past (B-52s and F-111s) when technology advances in radar and their processors allowed TF/TA capability. These early systems however presented data displayed to the aircrews in a format which were primitive to today's standards. Early TF/TA could only be performed manually by the aircrews and required the close attention of both the pilot and copilot. Modern TF/TA, although it can still be performed manually

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[13] The exact errors are not specified in this paper, but may be obtained from the Defense Mapping Agency. In real-time using radar altimeter data, the net vertical error used for GCAS/GPWS purposes can be reduced.

[14] A technique for projecting elliptical earth data to a 2-dimensional grid using a Lambert Conic Projection.

using superior displays (presented on multi-display units which allow changing the display on a given screen), can now be performed automatically and by only one crew member.

If an aircraft is equipped with a main/weapons radar which is TF/TA capable, it is used for low-level terrain-following missions to tell the aircrew what the terrain is ahead of the aircraft. In this instance, the radar is used in a slight look-down mode to scan forward and create a display of the upcoming terrain to the aircrew for maneuvering, or in some instances, send data to other systems which can automatically fly the aircraft above the terrain. The radar system must be in a specific mode to perform this Terrain Following/Terrain Avoidance (TF/TA) mission because other onboard systems must be brought together to perform the TF/TA task (e.g. flight controls, radar altimeter, navigation, etc.) and the radar must be dedicated to the TF/TA task. It is for this reason that TF/TA modes cannot be used for generic, all-purpose GCAS/GPWS, because while at low altitude, the aircraft need not be (and seldom is) performing actual TF/TA. Also, a majority of the aircraft involved in CFIT mishaps do not have the type look-down primary/weapons radar needed for terrain avoidance[15].

The quality and safety of TF/TA data depends very heavily on the quality (size, power, computational power, etc.) of the radar and avionics, as well as the strength of the radar return from the terrain/obstacle. Larger aircraft have more room for the antenna, radar computers, systems cooling, etc. In the past before great advances in radar and computer technologies, larger aircraft tended (though not exclusively) to perform the TF/TA specific missions (in addition of being able to carry larger payloads to the ground targets). Large aircraft such as the F-111, B-52, B-1, B-2 have systems onboard to specifically perform the TF/TA function (note: an auto TF/TA F-16D was flight tested at Edwards AFB in the mid-80s and may be adopted by the USAF in the future). Technology advances/miniaturization have enabled smaller aircraft, namely, the F-16C/D, F-15C, and F-22 to perform manual low-level flight in terrain, but these systems are not as "capable" as those designed for auto TF/TA. However, they can perform the manual low-level mission adequately. Three other fighter/attack aircraft, the F-16 LANTIRN, the F-117 Stealth Fighter, and the F-15E Strike Eagle are specially designed to perform all-weather/night attack. These aircraft rely upon external carriage of a FLIR pod/system and, except for the F-117, special purpose look-into-terrain radar in addition to the standard aircraft's radar to accomplish this critical mission (as stated previously, the F-117 is not equipped with a forward looking/ weapons radar.

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[15] As presented in *The Problem* section of this paper, 70% of CFITs were fighter/attack/recce which typically do not have TF/TA radar.

In auto TF/TA, a crew-specified ground-clearance altitude is set along with desired ride quality (soft or hard motions) and the aircraft automatically flies in the pitch axis above the terrain, staying above the set ground-clearance. A 2nd-order Taylor Series is applied to the radar-return terrain data to determine what is called the upcoming terrain's "critical point". The critical point is used to determine what g the aircraft must pull in conjunction with the crew specified ride quality and g-capability of the aircraft to not violate the specified altitude clearance altitude or to re-acquire the set altitude after an altitude excursion. Currently, no USAF active duty combat aircraft has the lateral-directional (roll/yaw) axis coupled with auto TF in the pitch axis. The experimental Advanced Fighter Technology Integration (AFTI) F-16 at Edwards AFB (the USAF's Flight Test Center), California however has the unique capability to automatically choose the minimum Mean Sea Level (MSL) route to a specified destination and use TF/TA to get there. There are developments underway to enable future USAF aircraft to scan ahead for terrain and pop-up threats/obstacles, compare the terrain to a stored map database which includes known ground threats/obstacles, and auto-fly the aircraft through the minimum MSL/lowest threat route, including mountainous terrain.

The auto TF/TF systems described above all have an emergency auto "fly-up" capability. This is when the radar altimeter comes into use for TF/TA (either auto or manual). An emergency fly-up (an auto-pull upward and disengagement of the TF/TA mode) command would be generated if there is a self-detected TF/TA system error severe enough to warrant a fly-up command, or if the set clearance altitude is busted longer than a predetermined (by system designer) interval as determined by the radar altimeter. An auto fly-up command could also be issued during manual TF/TA and would first be led by a "pull-up" warning (audio warning). Obviously, the "auto fly-up" and the "pull-up" warning are similar to GCAS and GPWS systems respectively.

The greatest difference between TF/TA warnings/fly-ups and GCAS/GPWS systems is that GCAS/GPWS systems must always be active, regardless of what mode or maneuver the aircraft is performing, whereas TF/TA is a very specific mode of the aircraft systems. GCAS/GPWS should not have to rely on the primary/weapons radar to avoid terrain/obstacles because most USAF aircraft involved in CFIT mishaps do not have a radar with the necessary capability. Also, if the aircraft does happen to have the necessary type radar, it may be performing tasks which do not look at the ground ahead (for example, looking up for adversaries), or may be in the standby mode (not transmitting). Finally, while at low-altitude, the aircraft may be maneuvering with bank angles exceeding 90 degrees, or possibly inverted, thus rendering the radar altimeter or main radar useless for TF/TA. Most radar altimeters have a beam width of roughly 45-60 degrees (Note: radar beams do not have uniform strength across the angle-off-center axis. The strength falls to zero at the edges). Extreme bank angles are especially common for fighter/attack aircraft - when cresting the top of a mountain to preclude "ballooning" across the descending terrain (and risk being seen by enemy radar), it is common to roll inverted and pull towards the terrain, down the back-side of the mountain.

All of the reasons just immediately discussed suggest that the most elegant and practical solution for GCAS/GPWS systems (and TF/TA for that matter) is the use of DTED maps in conjunction with a low "signature" (a term used to describe the magnitude of a target's radar return) sensor which looks for unmapped obstacles or performs INS updates.

GCAS and GPWS Specifics

The main problems involved in GCAS/GPWS systems are:

Where's the obstacle?
Where am I relative to the obstacle?
Where am I going?
How and when do I tell the pilot?

Where's the Obstacle and Where am I Relative to the Obstacle?

Aircraft must avoid: the ground; man-made objects such as towers, wires, and bridges; and natural obstacles such as trees. This problem can be solved using the tools described below.

The first (and most popular) tool used to identify terrain/obstacles is radar. The forward-looking primary/weapons radar scans the terrain ahead of the aircraft, though only some USAF are equipped with forward-looking radar capable of performing terrain avoidance while at low altitude. The majority of CFIT mishap aircraft between 1980 and 1993 were not equipped with such radar because they are extremely expensive (millions of dollars) and are not a requirement for most missions. Because of their size, power, and beamwidth, the forward-looking radar can identify most obstacles and terrain. However, depending upon the thickness of foliage and moisture content, in addition to the radar polarization/frequency, these radar may penetrate the foliage and miss some natural obstacles. This is rarely a problem however because typically for trees to be tall enough to be of concern, the radar would detect them and rarely would an aircraft be routinely flying low enough for trees to be a major problem. Although a small, lone tree can knock an aircraft from the sky, a tradeoff must be made between equipping aircraft with complex/expensive forward-looking radar which can identify <u>every possible</u> obstacle and the cost/mission requirements of the radar/processor. With the exception of power lines, man-made objects are usually easy to detect because of their flat, angular surfaces and the reflective materials they are constructed from. Power-line towers are usually detected by forward looking radar, but the wires may not. Radar altimeters point downward, thus do not look forward or sideways (in the event of banked flight). Their beamwidths are roughly 45-60 degrees, thus depending upon height above ground, they may look slightly forward/sideways but the strength of the beam at its edges is drastically reduced.

As discussed previously, because radar must be transmitted as well as received, it is open to jamming or worse yet, detection. Secondly, bank angles exceeding roughly 45 degrees present a problem to obstacle/terrain detection because at non-wings level flight, the radar altimeter may not "see" the ground below. The forward looking radar's performance will also be severely degraded at extreme bank angles dependent upon its look/heading angle capability. One solution to the bank angle problem may be to mount several radar altimeters in a manner to achieve the desired coverage (up to 360 degrees if desired, such as the A-10 aircraft) or better yet, install steerable radar altimeters (automatically compensate for bank angle up to the limit of the antenna). If very wide coverage is desired, more than one steerable antenna would still be required.

Forward-Looking Infrared (FLIR) is another sensor tool used to detect terrain and obstacles. It is employed on LANTIRN equipped aircraft, the F-15E, and the F-117. Because it is not transmitted, it is ideal for stealth tactics. However, for this same reason, ranging information cannot be ascertained. Instead, laser range-finders/targeting systems must be used to identify range. FLIR information is processed and displayed to the pilot in the form of a picture much like a visual picture for manual flight. FLIR is not currently used exclusive of other sensors for auto TF/TA or GCAS/GPWS, but future technology advances may increase their usefulness.

The most elegant solution to the terrain/obstacle detection problem is totally passive - Digital Terrain Elevation Data (DTED) stored terrain/map data. They are available for any place in the world and can be loaded into the equipped aircraft before or during flight. They are independent of the aircraft's attitude (bank angle, pitch, etc.) and are accurate enough for general GCAS/GPWS use. <u>Any</u> obstacle can be included in the DTED data assuming it was detected when creating/updating the map. New construction or significant terrain changes from the time a map was created or last updated could be a problem depending upon the altitude of the flight profiles. For flight over water, tides may need to taken into account in some areas, depending upon the elevation accuracy needed.

The AFTI F-16 Test Force at Edwards AFB and Lockheed Corp. (Ft. Worth Division.) have developed and demonstrated an auto recovery GCAS which uses stored DTED for terrain/obstacle avoidance. They suggest that if digital maps are used for TF/TA or GCAS/GPWS purposes, that extra memory be placed in map/processor to allow for real-time updating of the digital map. For instance, if a new pole or building has been erected since a map was created and the aircraft detects the new obstacle using the radar altimeter, or forward-looking radar, etc., then the coordinates and height of the new obstacle are placed in memory and used to update the map. Additionally, the AFTI F-16 Test Force states that the terrain height on these digital maps could also be updated for foliage growth or error correction. This is achieved by using accurate GPS/INS coordinates in conjunction with the aircraft's radar altimeter to correct any terrain height anomalies which might exist. Obviously, the accuracy and resolution of the "truth" sources would have to be greater than the digital map data itself.

The key to using DTED for terrain avoidance is knowing where the terrain/obstacle is relative to the aircraft with just enough accuracy. As will be discussed in detail in the Cost/Benefit section, there must be tradeoffs between GCAS/GPWS system complexity/cost against probability of CFIT mishaps. For instance, installing/retrofitting all USAF aircraft (or even just fighter/attack aircraft) with one of the following two items would not be practical: 1.) forward-looking terrain radar to either update navigation systems or detect obstacles would be both cost prohibitive and exceed mission requirements (most do not require this type radar to perform their missions adequately); or 2.) Extremely fine-grid DTED maps which include all obstacles and the necessary onboard computing power to handle this information would be cost and size prohibitive (especially when combined with a more accurate navigation system to resolve this finer grid). Perhaps installing a very simple/minimal GCAS retrofit system on all USAF aircraft is the best alternative of all possible alternatives? Maybe just on fighter/attack aircraft? Updating USAF aircraft with GPS/GPS up-datable navigation systems appears practical because of its potential use for other than just GCAS/GPWS purposes. Additionally, USAF studies regarding alternative methods to navigate, such as gravity variation mapping may also provide practical cost affordable solutions in the future. All these costs and real-world operational requirements must be weighed against the likelihood of a preventable CFIT mishap. It is estimated that less than 1 percent of total fighter/attack flying time is spent in the low-altitude environment. While in that environment, what are the chances of colliding with that one tree/obstacle not on the DTED map? Also, what do you gain by auto recovering or warning the pilot at exactly the right instant/position of an imminent terrain collision (using an over-designed GCAS/GPWS navigation system) if recovering just a little prematurely would suffice? All these will be studied in the Cost/Benefit section.

Where am I Going?

For GCAS/GPWS systems to be practical they need to know where the aircraft is going to be several seconds in the future, not just where it is now. Detecting a power-pole with the radar altimeter too late to avoid is useless. Terrain collision avoidance prediction is a complex problem and requires an onboard computer to continuously perform terrain avoidance calculations. Although specific terrain avoidance calculation/techniques proposed in the past vary with manufacturers (or USAF could require them to be the similar), those developed for the AFTI F-16[16] and demonstrated inflight are probably both the simplest (for adequate performance) and the most robust (able to handle unexpected anomalies). The following discussion and Figures IV-1, 2, & 3 provide a brief explanation of how these calculations are performed:[17]

1.) A simplified 200 meter spacing terrain model was derived from the Lambert Conformal Conic Transformed 100 meter spacing Digital Terrain Elevation Data (DTED) described earlier. Within each 200 meter grid-box is a "post" which is the highest elevation within each 200-by-200 box on the area map. The 100 meter grid however is retained and used for navigational purposes only, not for predictive flyup calculations.

2.) A "scan" pattern (subset) of the terrain data was calculated from the terrain map to acquire the grid "post" elevations within a scan region. The scan region was a function of aircraft speed, dive angle, bank angle, horizontal acceleration, and navigational uncertainty. See Figure III-1.

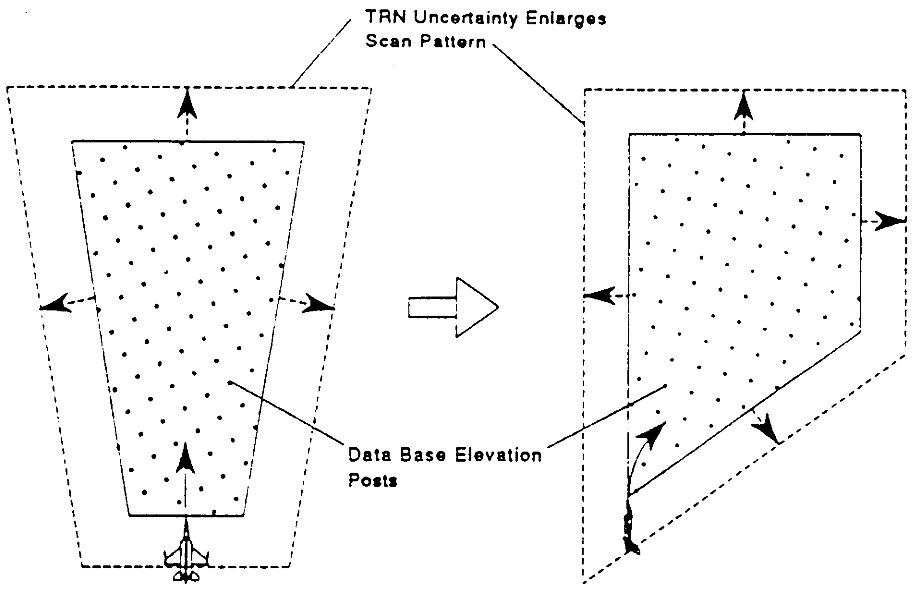

Figure III-1. GCAS Algorithm Scanning

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[16] The experimental Advanced Fighter Technology Integration (AFTI) demonstration aircraft at Edward AFB has developed and installed a GCAS system. They are the USAF leaders in GCAS technology. Appendix A of this paper contains a description and capabilities of this unique aircraft.

[17] *Controlled Flight Into Terrain*, USAF Flying Safety Magazine, Oct 1993, pages 20-21.

3.) The three dimensional scan region was simplified into a two-dimensional terrain "hull" made up of bins. See Figure III-2. Each terrain hull "bin" contained the maximum 200 meter spaced DTED post height from all posts which are equidistant from the aircraft at that moment.

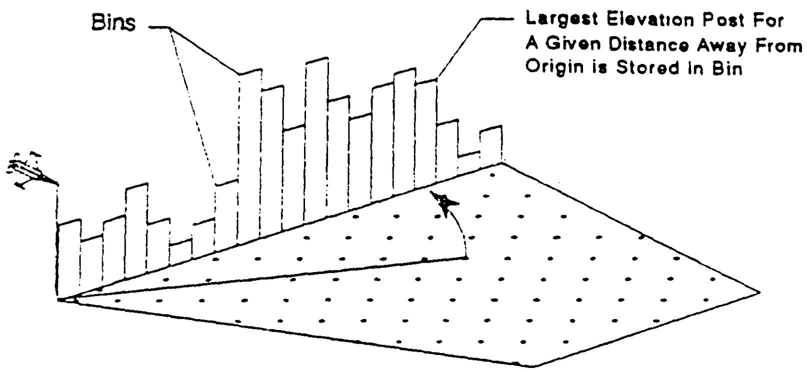

Figure III-2. GCAS Algorithm Binning

4.) Slopes are drawn to the binned DTED elevations of the array and the largest positive and smallest negative slopes are determined. A line is drawn connecting these points. This is called terrain hulling. See Figure III-3.

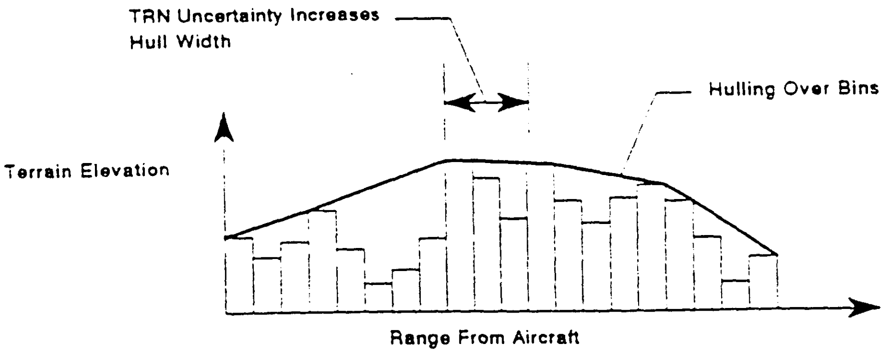

Figure III-3. GCAS Algorithm Hulling

5.) A predicted flight trajectory is computed from the Inertial Navigation System (INS) and a Time-to-Flyup is calculated, including the time it takes to roll the aircraft to wings-level flight prior to the automatic pull to recovery. See Figure III-4. The minimum distance, D is the minimum distance between the predicted aircraft trajectory and the simplified terrain hull. MCD is the pilot selected Minimum Clearance Distance (i.e. the minimum altitude the pilot will accept between the ground and the aircraft. The lower the MCD, the braver the pilot). When time to flyup reaches zero, an auto flyup command is sent to the flight control system. The aircraft is rolled to wings level (how fast depends on the store loading and limits of the aircraft), then the nose is brought up for the recovery and held for an appropriate length of time.

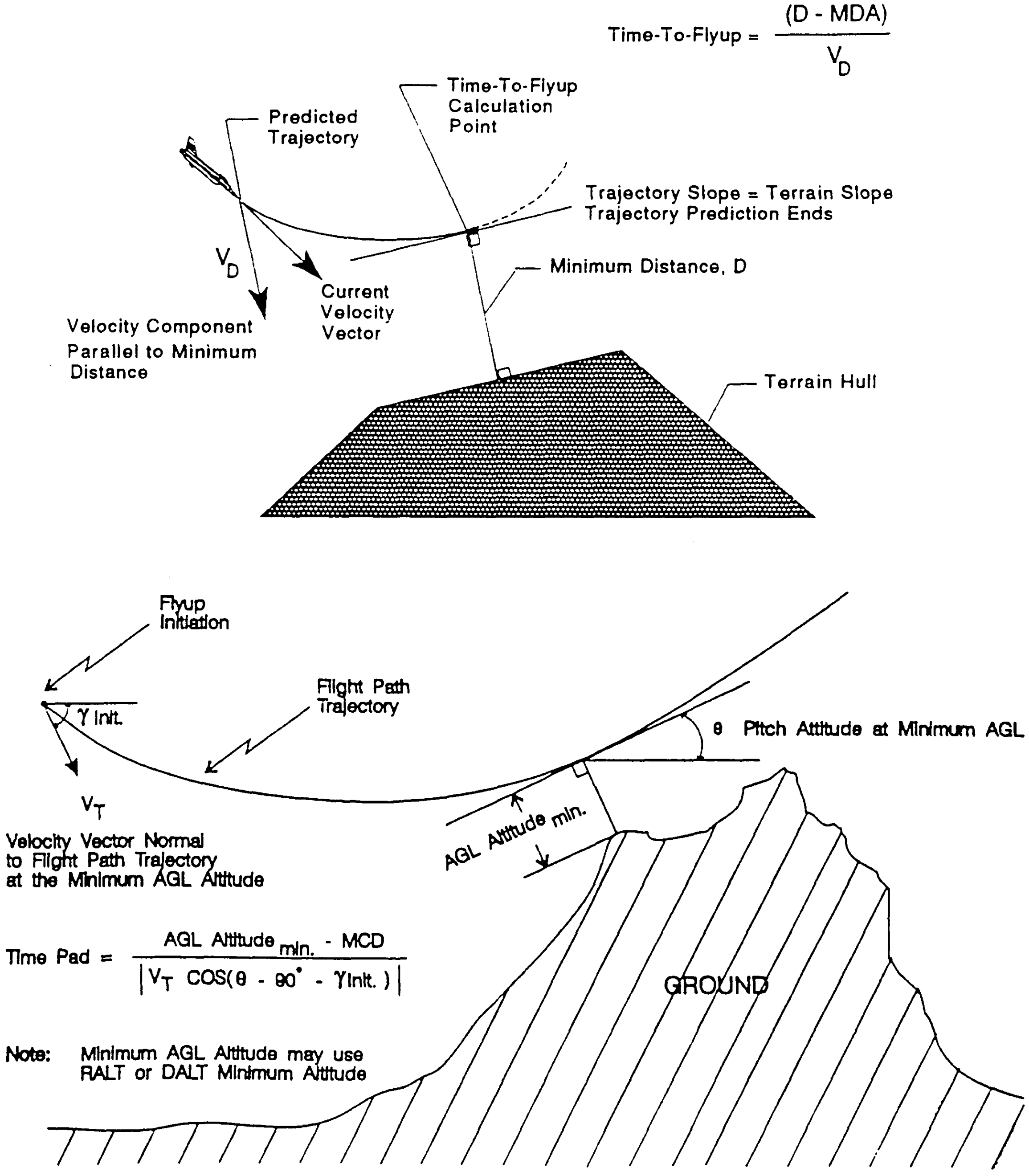

Figure III-4. Trajectory Prediction and Time-to-Flyup Calculations

As described, the time to flyup can be used on either an auto recovery GCAS system as on AFTI (a warning prior to auto flyup is desirable and will be described in the next section), or merely as a warning sent to the aircrew in the case of a predictive GPWS . It is important to point out that what is commonly referred to as GPWS systems usually do not have predictive calculations. Although some systems may predict the aircraft's trajectory, they do not "know" the upcoming terrain, instead, they estimate it based upon what is currently directly below the aircraft. As will be descibed later in this chapter, the F-15E GPWS operates using simple estimates of the upcoming terrain. Non-predictive GPWS only tell the aircrew when preset minimum altitudes are exceeded. In many circumstances this is adequate. If the terrain does not rise too rapidly, or the pilot is distracted and does not notice a slight descent over smooth terrain a non-predictive GCAS/GPWS may be adequate. Frequently, because of these limitations, non-predictive GCAS/GPWS systems have conservative minimum altitude limits which then lead to "nuisance" warnings to the pilot (described in next section).

How and When do I Tell the Pilot?

A GPWS system must warn the pilot of the obstacle and allow the pilot to maneuver the aircraft to avoid it, or in the case of GCAS, the aircraft should first warn the pilot, then take control of the aircraft at the last possible moment (and tell the pilot it is doing that). The main problem is that GPWS and GCAS usually conflict directly with what the aircrew wants. Pilots want the system to work in the cases where they need them to work (if distracted, target fixated, etc.), but yet not activate when they know exactly what is happening (intentional combat descent below predetermined GPWS "floor"). The problem is, the system has no idea whether the pilot is aware of an imminent collision or not.

GPWS:

A GPWS warning system is necessarily more conservative than an auto recovery system because the pilot must be warned of the obstacle and then be allowed enough time to react and maneuver the aircraft. How much warning is dependent upon the pilot's selected minimum desired altitude floor, the terrain, and the aircraft's state (attitude, velocity, etc.). One problem with only issuing a warning to the pilot is that he/she may not hear it. This problem was discussed in more detail in The Problem section of this paper. Many times the pilot may be so task saturated that the warning goes unheeded or in the case of GLOC, he/she cannot hear the warning at all. Another more common problem with GPWS is what are called "nuisance" warnings. These arise when the aircrew is bothered by warnings that are premature, unnecessary, or in error. For example, if a minimum altitude floor of 500 feet is set and the mission involves dive bombing where the aircraft may frequently bust the minimum altitude GPWS floor, the pilot will certainly call the unnecessary warnings a nuisance. Another example is in the case of F-15Es. Frequently the F-15E pilot wishes to get to a low altitude as quickly as possible (combat descent) and rolls the aircraft inverted and pulls towards the earth. The problem is, the GPWS determines a buffer altitude (altitude at which the GPWS is trying not to bust) higher than where the pilot desires to be and thus, sends the pilot a warning which the pilot deems to be a nuisance. On the F-15E, its GPWS determines the "buffer" altitude (minimum clearance distance) as a function of vertical velocity. If vertical velocity is zero (level flight), the minimum altitude is set near 50 feet. However, if the aircraft is in a rapid descent, the floor is much higher (approximate exponential function with vertical velocity).

Current GPWS systems:
All GPWS systems currently utilized in USAF aircraft are, at most, pseudo-predictive (they do not predict the aircraft's trajectory into the future relative to the **actual** upcoming terrain). They may predict the aircraft trajectory, but do not "know" the upcoming terrain. For example, the F-15E's GPWS uses present and past returns from the radar altimeter (has only one) to compute the existing slope of the terrain and extrapolate that slope forward in an attempt to provide ample warning to the aircrew. The algorithm does use current aircraft state parameters to predict its state into the future, but relative to an unknown terrain.

Past algorithms developed by contractors or USAF labs in the past were not adequate. They either had too many nuisance faults, were not robust enough, or did not work in simulation. For the purposes of this paper, I do not include TF/TA systems in the GPWS/GCAS category because these are "special" modes of the aircraft and are not operating in the background from takeoff to landing. The existing GPWS systems rely upon the radar altimeter and/or air data derived altitude to provide warning to the aircrews. The GPWS used today can be found in transport/bomber aircraft and are mainly used for approach/landing. They are also utilized somewhat on fighter/attack aircraft by the pilot selecting a minimum Above Ground Level (AGL) floor and relying upon the radar altimeter to determine when this floor is penetrated. Fighter/attack aircraft however seldom rely upon the feature to prevent CFIT because of nuisance errors and warning inadequacy. The radar altimeters provide only direct look-down capability and are adequate up to bank angles of roughly +/- 30-45 degrees.

The F-117 has a unique capability installed as a result of its special night mission. As discussed in the Human Factors portion of this paper, spatial disorientation (SDO) is a valid concern when flying at night. Since the F-117's mission is almost exclusively a night mission with maneuvering, the aircraft is equipped with a Pilot Activated Recovery System termed "PARS" which is coupled with the aircraft's autopilot. Upon pilot activation of the PARS in the event of disorientation, the aircraft rolls to wings level and pulls away from the terrain. As will be discussed in later portions (GPWS and GCAS Initiatives) of this chapter, this PARS function is gaining acceptance by the USAF for use in other aircraft in the near future.

Auto recovery/GCAS:
If nuisance errors can be eliminated or reduced to an insignificant number of occurrences, then auto recovery/GCAS is the preferred system. Both GPWS and GCAS system requirements are nearly identical assuming they are both flight path predictive, therefore the cost of each are close. The biggest difference between the two systems is that GCAS must be meshed with the aircraft's flight control system. Doing this means that the GCAS system must have the same stringent system redundancy and system self-check requirements as the flight control system, On modern digitally controlled aircraft, the flight control systems are quad-redundant and the self-check algorithms are complex, so adding-in the GCAS can be intensive and more costly than GPWS.

Nuisance faults in GCAS systems can be particularly bothersome and in some cases dangerous (flying in formation with another aircraft, or during landing/takeoff, etc.) even if the pilot has GCAS-override capability. For this reason, GCAS systems must be more accurate and dependable than GPWS, both of which cost money to develop and test, as will be described in the Cost/Benefit section of this paper.

Obviously, GCAS must be a predictor system. It should warn the aircrew before taking control of the aircraft. It must then quickly roll the aircraft to wings level and pitch up, pulling an "adequate" number of g's, and then return to level flight or disengage after an appropriate length of time. The pilot must also be able to override the auto-recover portion of GCAS at any time. Some pilots perceive a GCAS system as an attempt to circumvent their God-given right to kill themselves perfecting new tactics or being the "hottest stick" in the squadron. The AFTI F-16 Test Force at Edwards AFB (the USAF's Flight Test Center), California have tested an auto recovery GCAS developed by Lockheed Corp. (Ft. Worth Division, formally General Dynamics Corp.) and have some recommendations regarding how best to implement a GCAS on fighter aircraft[18]. The aircraft was tested against smooth earth and mountain terrain, and at various dive and bank angles. A few of the key conclusions and recommendations are as follows:

1.) Auto GCAS is much preferred over GPWS by the pilots (by large majority of those that flew the AFTI system). "The recovery maneuver provided an immediate and precise recovery to a known termination condition. The automated recovery

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[18] Details are included in the Air Force Flight test Center (AFFTC) Technical Report (TR), TR-93-07, Sept 93, entitled, *AFTI F-16 Close Air Support Block II/III Automated Recovery System Evaluation*, pages 41-46 and 141-148.

demonstrated repeatability which inspired confidence in the system and increased maneuver awareness."[19]

2.) Nuisance errors should be eliminated by upgrading the computer and algorithms to allow for faster/more detailed iterations of the digital map and Time-to-Flyup calculations. The implementation philosophy was correct, just needed more powerful computers to eliminate the occasional nuisance error.

3.) The judgment was divided by the test pilots on whether the Minimum Clearance Distance (MCD is the lowest altitude at which the aircraft will come to the ground during the auto recovery) should be pilot selectable. Some felt that it should automatically be selected based on type of terrain (smooth, moderate, or rough/mountainous), mission (strafing, bombing, etc.), navigation accuracy, etc. Others felt the pilot should have complete control of such an important parameter.

4.) Due to limitations of the production F-16 (INS drift), the correlation between perceived position on the digital map and true position sometimes induced less than desired performance (but the algorithm always compensated in the conservative/safe direction). This was especially true over mountainous terrain where radical fluctuations in the radar altitude degraded the navigation systems ability to correlate INS position with the digital map position. However, these could be eliminated (or significantly reduced) using GPS coupled INS or some similar upgrade to the nav. system (a GPS alone system could be "spoofed" which would be unacceptable for war-time). In rough terms, the terrain navigational resolution using DTED without GPS is slightly better than the DTED resolution. Therefore, if the DTED navigational database is 100 meters, the navigational error was slightly larger than 100 meters.

5). The most the aircraft ever "busted" or penetrated below the Minimum Clearance Distance over flat terrain was 12 feet and on average, the flyups came within 73 feet of the MCD. Over rough/mountainous terrain, the there were no penetration of the MCD and on average, the flyups came within 401 feet of the MCD. These errors were attributable mostly to the navigation system errors discussed in item 4. above.

6.) The Heads Up display (HUD) symbology/ system mechanization and auditory warnings of the auto recovery used in AFTI are recommended. Two "Chevrons" (sideways "V"s, > and <) in the center of the display move together as the impending auto flyup time is approached. When the "chevrons" touch to form an "X", the flyup occurs, accompanied by an auditory "Flyup, Flyup" warning.

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[19] AFTI F-16 Test Pilot.

7.) "A simple, concise, and reliable GCAS is the only acceptable option for the user. We must build the system for the lieutenant flying on the wing at low altitude in marginal weather conditions. We are very close. For me, a totally reliable system from a system operations standpoint is # 1 priority, # 2 priority is the elimination of perceived nuisance flyups."[20]

Current GCAS:
With the exception of the experimental AFTI F-16, there are no operational auto recovery GCAS systems onboard USAF aircraft. Although the F-117 is equipped with PARS, as the name implies it must be activated manually by the pilot and also uses a flat earth assumption in its algorithm.

GPWS and GCAS Initiatives

Many System Program Offices (SPOs), including the F-16, F-15, A-10, B-1, B-2, F-117, and new F-22 (first flight currently scheduled for 1997) are aware of the CFIT mishap problem and the CSAF's (Chief of Staff, Air Force) desire to equip USAF fighter/attack aircraft with GCAS/predictive GPWS. These SPOs have programs currently underway, or have plans to correct the problem. The F-22 program has sent a Statement of Work to Lockheed requesting a pricing of adding an auto-recovery AFTI type GCAS to the baseline aircraft[21]. Depending upon the contractor's price, the F-22 program will then determine whether to add the cost in the next Program Objective Memorandum - POM (a DoD budgeting document) or add it as a follow-on project in the future. The cost to add the auto-recovery GCAS is basically just a change in software to the avionics and the flight control Operational Flight Program (OFP). The aircraft is not equipped with a radar altimeter for stealth reasons, therefore since the current baseline F-22 will be equipped with GPS, the plan is to use GPS coupled with the aircraft's Inertial Navigation System as a reference for the DTED map (the F-22 is also equipped with a Mega DTC capability as a baseline article). With the GPS/INS reference, the number of nuisance errors evident in AFTI when flying over rough terrain should be greatly reduced.

The F-15E System program Office has been working on a GPWS for 4 to 5 years and in 1994 tested the system[22]. The Mac-Air developed GPWS algorithm resides within the aircraft's Operational Flight Program (OFP) and works in conjunction with the aircraft's lone radar altimeter (thus does not function accurately during extreme bank

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[20] USAF AFTI F-16 Test Pilot

[21] The information regarding the F-22 program plans to implement GCAS were obtained in an interview with F-22 program personnel.

[22] The information regarding the F-15E program was obtained through an incrview with a program manager within F-15 System Program Office (ASC/VFWA).

angles). The GPWS uses present and past radar altimeter data to compute the slope of the terrain under the aircraft and extrapolates the slope forward of the aircraft. The minimum clearance altitude (the altitude the system is trying to stay above) is computed as an exponential function of vertical velocity. Basically, the system was designed to protect the crew during typical, common maneuvering and was priced at roughly $3.4 Million for software development and DT&E testing. The system passed Development Test and Evaluation (DT&E) conducted at Edwards AFB in 1993-94, but did not pass Operational Test and Evaluation (OT&E) in 1994. Some personnel felt the type and number of maneuvers utilized during OT&E were more extreme than required, causing more nuisance errors than acceptable. For example, nuisance errors cropped up during combat descents (very aggressive dive to the earth) where the pilot intentionally dives the aircraft towards the earth and has predetermined the pullout initiation altitude in the mission plan, but which is below the GPWS warning altitude (remember, this is a function of estimated slope, vertical velocity, and radar altimeter last update time). The failure of not passing OT&E goes to the heart of the problem with GPWS/GCAS. The system may operate when not desired because it doesn't know that the pilot is aware and wants to do something which could exceed the minimum clearance altitude. Because the system estimates the upcoming terrain, coupled with the fact that the crew must be given ample warning (1 to 2 seconds), nuisance errors are likely. Work is currently underway to reduce the number of nuisance errors in the F-15E system and testing is expected to resume in Sept 95 with the release of the next OFP. Plans include adding a "on/off" switch in the cockpit giving the pilot the option of turning the system off.

Within the next few years, an effort is underway to upgrade existing F-16 aircraft which are currently equipped with digital Data Transfer Cartridges (DTC), with newer "Mega DTCs". As will be explained, upgrading to Mega DTCs gives aircraft the capability for predictive GCAS/GPWS. Some aircraft in the active duty USAF inventory are currently equipped with DTCs for the purposes of loading and reading mission plans. These aircraft include the F-16, F-15E, B-1, B-2, F-111, and F-117 (basically, any aircraft with digital avionics/flight control systems or analog to digital interfaces). With the current DTC system, prior to takeoff or inflight, a cartridge which contains navigation, mission routing, and target information is loaded into the DTC system. To aid the pilot in navigating during the mission, these aircraft use this cartridge data and other onboard systems (radar, TF/TA, etc.) to help auto fly the aircraft or display data to the aircrew for manual flight. Currently, the data capability of these DTC data storage are not large enough for a DTED database, thus they must be upgraded. Advancements in data storage have now made it possible to store the DTED map data as well as other functions in the same size cartridge as currently exists, thus precluding the need to modify the reader already installed onboard USAF aircraft. With a new cartridge which fits in the old reader, the aircraft can then access DTED data.

Oddly enough, this upgrade to active-duty USAF aircraft came about by initiatives from the USAF Reserves and the Air National Guard (ANG) to incorporate an AFTI F-16 auto GCAS system on their aircraft. After receiving a briefing from the AFTI F-16 program, the Commander of Air Force Reserves gave the go ahead to begin a program to modify all existing Reserve fleet F-16s aircraft with auto GCAS capability (Note: the Reserve and ANG are equipped with older, analog F-16 aircraft - Block 30 type and previous OFP versions). As a result, a "Mega DTC" was spec'd by the Reserves using AFTI F-16 developed software. Simultaneously, the active duty Air Force had disjointed studies and initiatives among nearly all fighter/attack aircraft SPOs to modify their aircraft with an upgraded GPWS over what currently exists on their respective aircraft. In order to reduce the per unit cost of the Mega DTC below that specified by the Commander of the Reserves, the Reserves approached the ANG and the USAF F-16 SPO (equipped with digital F-16s) and convinced them to join efforts in acquiring the Mega DTC. The USAF then decided to upgrade all F-16 DTC equipped aircraft with the Mega DTCs in the future beginning in 1997 following development and flight test.[23].

The Mega DTC contains the following capabilities:

- Digital Terrain Elevation Data (DTED)
- Terrain Referenced Navigation (TRN) needed to navigate using the DTED
- Manual TF capability cued by DTED/TRN
- Predictive GPWS (GCAS terrain hulling and flyup computation only. No auto flyup because flyup command/maneuver must be connected to flight control system for auto recovery)

The F-16 upgrade to achieve GPWS capability is much needed as evidenced by the frequency of F-16 CFIT mishaps. Currently, F-16s have very cursory ground collision advisory warnings sensed by the radar altimeter or the weapons radar (during air-to-ground weapons delivery mode). As a result of many factors, including mechanization, collision predictive algorithms, HUD symbology, etc. the current system is unsatisfactory. Except for the ongoing upgrade to GPWS capability, there is no plan to upgrade the active duty USAF F-16s with an auto-recovery GCAS. To achieve auto-recovery capability, the F-16s flight control OFP would require upgrading (to implement the recovery software) and at this time, there are no plans to do so (the latest was recently released to the fleet). A new OFP release costs approximately $30

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[23] Data regarding USAF F-16 GPWS implementation was collected in interview with program manager within F-16 System Program Office (ASC/YPT)

million to $40 million. Flight testing of the Mega-DTC held GPWS is estimated at $5 million.

However, before the AF Reserves can have auto-recovery GCAS, the aircraft must be equipped with an upgraded Digital Interface Card (DIC) which, as the name implies, interfaces with the DTC and the aircraft's analog flight control system. Due to circuit miniaturization advancements, it is now possible to include not only the necessary analog to digital conversion on a single DIC, but other software as well. This "other" software is the auto recovery portion of the GCAS. Also included in the Reserve's DIC upgrade is the Pilot Activated Recovery System (PARS), discussed earlier, which is currently employed on the F-117. So, the new Mega DTC combined with the Reserve's DIC upgrade will give the AF Reserves a full auto recovery GCAS and PARS capability. The USAF F-16s however will only have the Mega DTC capability (predictive/warning GPWS) because their aircraft must either upgrade their digital flight control system Operation Flight Programs (OFPs) with the auto recovery software and PARS software or else acquire the upgraded DICs.

In summary, once a USAF aircraft is updated with only the Mega DTC (not upgrading the flight control OFP or upgrading the analog/digital Digital Interface Card-DIC), the aircraft will have predictive GPWS capability using DTED for terrain referencing. Until a modification is made to the DIC or upgrade to the flight control OFP, they will not have protection for GLOC, nor the Pilot Activated Recovery System-PARS in the event of disorientation.

It is unfortunate that the entire USAF has not made a decision to implement the Mega-DTC upgrade on all existing DTC capable aircraft (F-15E, B-1, etc.). Instead, each aircraft program must develop and field individual, unique GPWS/GCAS systems for their aircraft. There are many advantages to a common GPWS/GCAS "core" across the entire USAF fleet - reduced development costs, common hardware (reduced logistics and maintenance), common mechanization to the aircrew, etc. Obviously, not all of the GPWS/GCAS components would be common throughout the USAF (different warning mechanization, slightly different software to account for avionics differences, etc.), but they would be similar. In addition, each program would be required to test the system because each aircraft type is unique.

What Terrain Reference Navigation system would best satisfy USAF requirements to align the DTED data (from the Mega-DTC) with true aircraft position? Currently, nearly all USAF aircraft are equipped with a radar altimeter, but many are being fitted with GPS. Although GPS coupled with Terrain Referenced Navigation (TRN) would decrease the inherent navigation error associated with DTED alone, it is not an absolute requirement. The Air Force Reserve effort to acquire auto GCAS does not involve

GPS. As mentioned earlier, the navigation accuracy demonstrated by AFTI F-16 was roughly the same as the DTED navigation resolution (100 meters). In most instances 100 meter accuracy is adequate, but in rough terrain, more accurate knowledge of true position may be required. Additionally, in general, the more accurate the navigation data, the less the number of nuisance flyups which might be caused by position error and the lower the difference between the actual recovery altitude and the pilot selected Minimum Clearance Distance. Thus, in the future once USAF aircraft are equipped with GPS and the new Mega-DTC, a more accurate system than the AFTI F-16 predictive GPWS may be possible and cost effective.

Summary of GCAS and GPWS, Advantages/Disadvantages

GCAS systems are more capable than GPWS systems in that they utilize auto recovery in addition to warning the aircrew. If the aircrew does not react to warnings of an immanent collision with terrain or an obstacle, the aircraft systems will wait until the last possible moment and automatically fly the aircraft away from the danger. The data presented in the summary part the previous section, The Problem: CFIT chapter II, showed that out of the 229 CFIT mishaps between 1980 and 1993, 165 (72%) of them would probably have been prevented if the aircraft had been equipped with a GCAS system[24]. In comparison, 129 (56%) CFIT mishaps would have been prevented if the aircraft were equipped with a predictive GPWS system. I would suspect the difference of 36 mishaps between the two systems should be slightly larger than estimated by the USAF Flight Safety Office because of the problem surrounding distractions. As described previously, at times aircrews will not hear warnings or take action when presented with a warning while in the midst of performing one or more very demanding tasks. This is referred to by human factors experts as "task saturation". As a result, a GPWS warning may go unheeded by a pilot and result in a CFIT, even though the aircraft is equipped with a GPWS. However, had that same aircraft been equipped with a GCAS, the same mishap may have been prevented.

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[24] Probable preventable CFIT mishap estimates (if aircraft were equipped with either GCAS or GPWS) were obtained from the USAF Flight Safety office, HQ AFSA/SEFF, Kirtland AFB briefing, *Controlled Flight Into Terrain USAF History*, Jan 1994. They assume a hypothetical "adequate" system.

Table III-1. GCAS

Advantages	Disadvantages
- Prevents larger number of CFITs than GPWS (72% vs 56%), including GLOC-caused mishaps. - Is "Predictive", thus prevents greater number of CFITs - AFTI F-16 as already developed workable system for fighter/attack aircraft. - If you're going to install a predictive GPWS, might as well install GCAS for a little more effort/cost.	- Nuisance errors must be eliminated (high reliability and accuracy). - Must be "wired" to flight control system, thus costing money and system complexity - 360 degree bank angle coverage requires multiple radar altimeters. - Probably not as useful on transport/bomber aircraft because of low g-capability for flyup, dual crew, and most mishaps are in approach/landing

Table III-2. GPWS

Advantages	Disadvantages
- Probably prevents approx. 56% of CFIT mishaps. - Predictive GPWS is certainly more robust than non-predictive (but cost more and more difficult to implement than non-predictive) - They are better than nothing.	- Crew may not hear or heed warning - Non-predictive warning may not do any good (too late for recovery/safe ejection) - They are utilized today. but we still have too many CFIT mishaps - Is prone to over simplification (to save time and $), thus prone to more nuisance errors than a well developed GCAS - Not as robust as GCAS, especially in fighter/attack aircraft. - 360 degree coverage requires multiple radar altimeters.

Table III-3. Digital Terrain Elevation Data (DTED) vs. Active Sensors

Advantages	Disadvantages
- GCAS using digital terrain data is passive (no electromagnetic emissions) - Contains obstacles which may not be detectable by airborne radar. - "Knows" what terrain is around aircraft which would normally not be seen by sensors (shadows/blank area behind mountains) - Is un-jammable by adversary unless also using sensors which are "spoofable" (e.g. GPS) - Meshes well with other USAF initiatives to use DTED on aircraft (mission planning) - Can be used for purposes other than GCAS (navigation at night /in weather)	- Requires source to update the navigation solution and correlate with digital data. - Map needs periodic updating to capture new construction or changes in terrain - Requires mass storage and fast processor capability - Generally not as accurate as other navigation data.

What do the preceding three tables and data in this section tell us? Technology is available today for GCAS or at least predictive GPWS that could be installed on USAF aircraft, beginning with fighters and attack aircraft. Clearly, based on the CFIT data presented earlier, the current GPWS systems are not adequate to significantly reduce CFIT mishaps. Although the numbers of CFIT mishaps has been decreasing for the past four years, the rate is increasing (because the number of total flight hours is decreasing faster). Couple this fact with the dramatic rise in cost of modern USAF aircraft, where if just one of these aircraft is lost due to a preventable CFIT mishap, the USAF and US taxpayer has lost tens or hundreds of millions of dollars. The majority (72%) of the past 14 years worth of CFIT mishaps could likely have been prevented if the aircraft were equipped with GCAS.

How much would it cost to retrofit USAF aircraft with GCAS? With the Mega DTCs? How much would it cost if included in the original procurement? How much does it cost the USAF and the taxpayers as a result of CFIT mishaps? How much can be saved as a result of GCAS? The next chapter will more fully analyze the cost, development requirements, and cost benefits of GCAS to the USAF.

IV. GCAS COST/BENEFITS AND FEASIBILITY ANALYSES

How much do USAF aircraft cost? The first two columns of the table below present these figures. The third column is the percent of these aircraft involved in CFIT mishaps between 1980 and 1993 as shown previously in Figure II-8.

Table IV-1. Cost of USAF Aircraft Involved in CFIT Mishaps[25]

Type Aircraft	Cost in $ Millions	Percent CFITs
T-37	0.185	2
T-38	1.2	2
Helo	4.0	11
C-130	5.2	5
F-4	2.9	14
A-7	3.1	7
KC-135	7.0 *	3
Misc.	5.0 *	6
A-10	5.3	13
B-52	7.3	2
F-111	8.0	4
F-16 C/D	13.6	23
F-15 C/D	15.6	7
F-117	30.0 *	0.5
B-1	215.0	0.5
		100

Note: Various models within a specific aircraft type (for instance, C-130 A, H, U) are averaged to obtain these cost figures.
* Estimate.

Not all of the 229 CFITs between 1980 and 1993 resulted in destroyed aircraft (172 were Class A-destroyed mishaps and 5 were Class A). Applying the percent CFIT mishaps for each type aircraft (third column from above table) to the total number that were destroyed, 172, yields the number of aircraft that were destroyed by type.[26] This is shown in the second column of Table IV-2 on next page. The third column is the resulting cost to the USAF per aircraft type (number of a specific type CFIT mishap aircraft times cost per a/c from Table IV-1). Lastly, the fourth column is the percent of total cost due to each type aircraft's CFIT mishaps.

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[25] Data obtained from USAF Safety Office, HQ AFSA/SEFF

[26] Data were not obtained on the number of aircraft that were Class A, B, or C, broken out by type aircraft. Only the total CFITs and total number of Class A, B, or C mishaps.

Table IV-2. Class A - destroyed CFIT Costs (costs are <u>not</u> per a/c)

Type Aircraft	# Aircraft in Class A CFITs[27]	CFIT Aircraft Cost ($M)	% Total CFIT Aircraft Cost
T-37	3	0.56	0.04
T-38	4	4.8	0.3
Helo.	19	76.0	5.2
C-130	9	46.8	3.2
F-4	24	69.6	4.7
A-7	12	37.2	2.5
KC-135	5	35.0	2.4
Misc.	10	30.0	2.0
A-10	22	116.6	7.9
B-52	3	21.9	1.5
F-111	7	56.0	3.8
F-16 C/D	40	544.0	37.0
F-15 C/D	12	187.2	12.7
F-117	1	30.0	2.0
B-1	1	215.0	14.6
	172	1,470	100

Table IV-2 above shows the total estimated cost to the USAF as a result of CFIT-caused Class A-destroyed aircraft from 1980 to 1993 was nearly $1.5 Billion. This does not include the cost of the remaining 5 Class A mishaps (costs are unknown) nor the remaining 57 Class B and C mishaps (costs are unknown). Note that F-16 CFIT mishaps contributed 37 percent of the total CFIT mishap costs, yet they represented 23 percent of the CFIT mishaps (see Figure II-8.). Similarly, the F-15 contributed 13 percent of the cost, but were only 7 percent of the CFITs. This is due to F-15/F-16 higher prices as compared to the older vintage aircraft which contributed to the CFIT mishaps. This highlights the projected rising cost of CFIT mishaps as newer aircraft begin to contribute to the CFIT mishaps. This is further evidenced by the expensive LANTIRN equipped F-16 mishap in 1994 not included in this 1980-1993 data.

These cost figures in Table IV-2 do not include the training costs associated with the crew members which were fatalities. As stated in Chapter II, a reasonable estimate for aircrew training is between $0.5 million and $4 million, depending upon rank and experience of the aircrew. Though not all of the 177 CFIT Class A destroyed mishaps resulted in fatalities, by far the majority did (out of the ejection seat envelope or there was no attempt to eject). The 176 CFIT fatalities between 1980 and 1993, times a conservative $1 million per aircrew member, equates to a loss of $176 million from 1980 to 1993 in addition to the aircraft costs shown above.

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[27] Number of Class A mishaps (172) multiplied by percent CFIT by aircraft type.

Up to this point, past USAF mishap data has been presented. What can we say about the probability and cost of CFIT mishaps in the future? To perform this analysis, the first step is to compute the probability of CFIT mishaps for each type aircraft. One way to do this would be to divide the number of CFIT mishaps from each type aircraft (F-16, or F-15, or B-1, etc.) by the total number of flying hours for that type aircraft to obtain the likely number of CFIT mishaps per flight hours. This is only statistically realistic if there is a large enough sample time and sample size. Since the USAF has recently acquired new types of aircraft with relatively few flight hours (for example, the B-2 and C-17) or is in the process of developing new aircraft (F-22), these new aircraft do not have a large enough (if any) sample size of flight hours. A more realistic method to compute CFIT probabilities would be to delineate the 1980-1993 data by "classes" of aircraft such as fighter/attack, bomber, transport, etc. and then apply the resulting mishap rate to the more modern/new aircraft to estimate their likelihood of CFITs. These data are presented in Table IV-3 and Figure IV-1 for the period 1983 through 1993. *Note: see Table IV-4 to determine how the aircraft type are categorized by class.* Helicopters are were intentionally omitted from the data due to their unique mission and characteristics which are outside the scope of this study. Table IV-3 shows the yearly number of USAF Flying Hours by aircraft class from 1983 through 1993. The table also shows the number of CFIT mishaps for these class aircraft and the resulting yearly CFIT mishap rates.

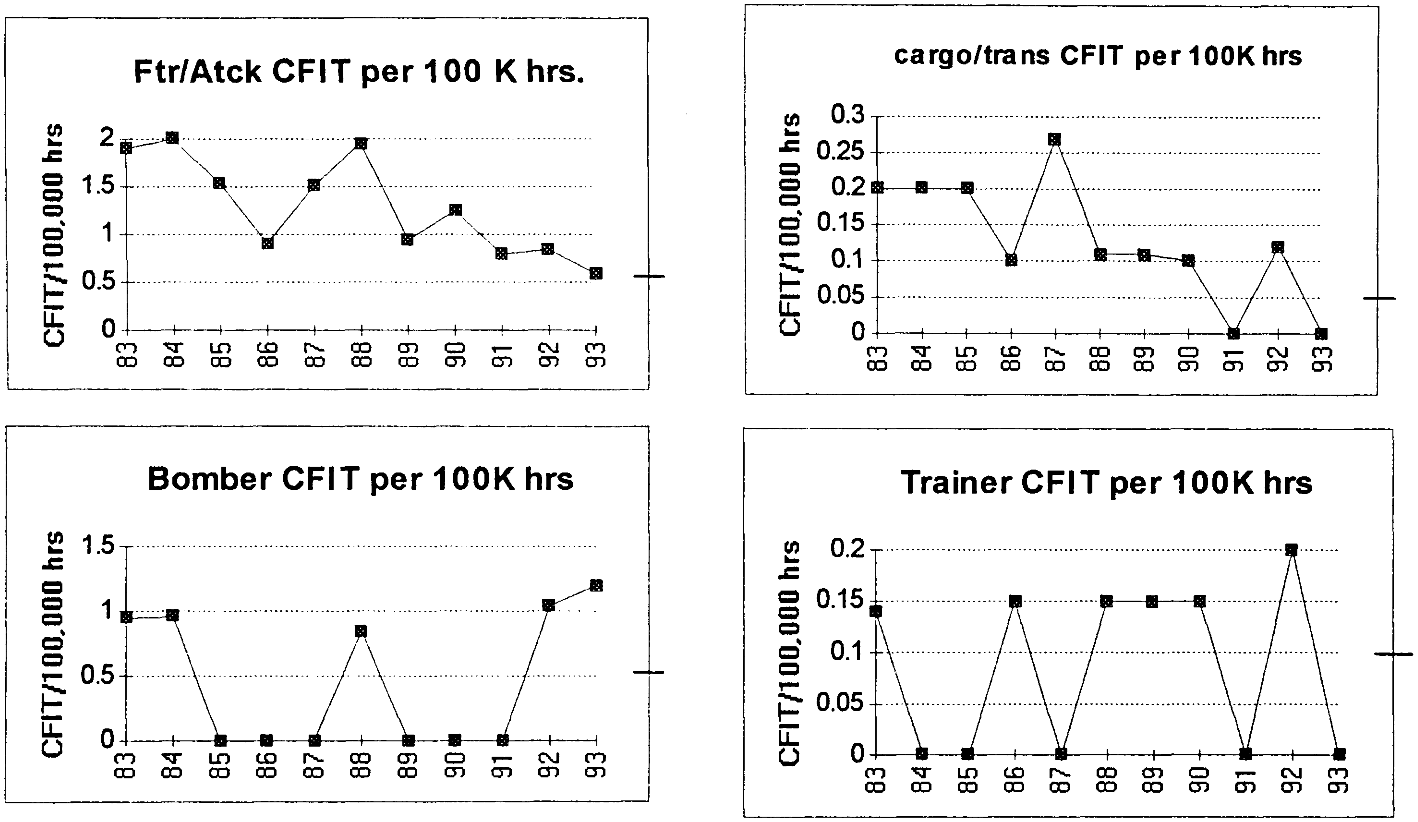
Once the probabilities of CFIT mishaps for each class of aircraft are estimated, the next step in estimating the future impact CFITs will have on the USAF is to compute the likely resulting cost of the mishaps. Table IV-4 is used to compute the weighted average cost of the four classes of aircraft by multiplying the cost of each type aircraft with a given class, times the weighted average of the number of aircraft of that type. The last column of the table, labeled "*weightcost*", represents the weighted cost of each type aircraft. The last column of the rows labeled "*Total*" represents the average cost for each class of aircraft. For instance, the average price of a fighter/attack class of aircraft is $30.28 million, a bomber is $125.2 million, etc. The author acknowledges the fact that the future "makeup" of the USAF fleet may not be represented by what is in Table IV-4 because some aircraft will be phased-out as new ones become operational. However, the table is only intended to estimate the average price of each aircraft class within the next ten years or so. It was constructed to be on the conservative side of costing (i.e. underestimate the price of aircraft) so as to not make future CFIT mishaps overly costly. The table underestimates the future pricing within each class because the data are weighted with older, cheaper aircraft which will be phased out of the fleet (creating a series of tables for the fleet makeup in each of the next ten years is futile). In addition, the cost of the aircraft in Table IV-4 reflect the cost of the baseline aircraft and does not include the cost of any avionics upgrades.

Table IV-3. CFIT Mishap Rate by Aircraft Class

	Year	Ftr/Attck	Bomber	Cargo	Trainer
No. of CFITs	83	17	1	2	1
	84	19	1	2	0
	85	15	0	2	0
	86	9	0	1	1
	87	12	0	2	0
	88	20	1	1	1
	89	10	0	1	1
	90	13	0	1	1
	91	9	0	0	0
	92	8	1	1	1
	93	5	1	0	0
Total Fly Hrs.	83	895743	104866	985928	696727
	84	951876	104128	971392	694000
	85	978300	106109	996184	675650
	86	997641	105057	972784	662044
	87	792377	88373	750834	507771
	88	1026658	117705	920292	669394
	89	1062898	126616	944175	684131
	90	1046617	117742	988321	668763
	91	1138769	114809	1308767	616727
	92	941379	96026	863651	500199
	93	843530	83472	827460	403075
CFIT Rate per 100,000 fly hrs.	83	1.90	0.95	0.20	0.14
	84	2.00	0.96	0.20	0
	85	1.53	0	0.20	0
	86	0.90	0	0.10	0.15
	87	1.51	0	0.27	0
	88	1.95	0.85	0.11	0.15
	89	0.94	0	0.11	0.15
	90	1.24	0	0.10	0.15
	91	0.79	0	0	0
	92	0.84	1.04	0.12	0.20
	93	0.59	1.20	0	0
	Mean	1.29	0.45	0.13	0.09
	Std Dev.	0.51	0.53	0.08	0.08
	Trend *	0.56	0.54	0.05	0.10

* Trend was computed using "TREND" function in Excel software which is a linear regression extrapolation to the year 1994.

Figure IV-1 presents plots of the CFIT mishap rate (per 100,000 flight hours) for the four aircraft classes (fighter, bomber, cargo/transport, and trainer).



Note: the "-" line on right side of each plot is the "trend" value shown in table IV-3

Figure IV-1. CFIT Mishap Rate (per 100,000 flt hrs)
for Aircraft Classes (fighter, bomber, cargo/trans, and trainer)

Table IV-4. Cost of Various Aircraft - by Class

Ftr/Attack

Type	Cost ($Mil)	Number	% of Total	weightcost
A-10	5.3	126	6	0.30
F-16C/D	13.6	499	19	3.03
F-16 lantirn	25.0 *	226 ***	11	2.52
F-15C/D	15.6	485	23	3.38
F-15E	29.6	204	10	2.70
F-22	80.0 **	442	21	15.80
F-111	8.0	135	6	0.48
F-117	30.0 *	54	3	0.74
F-4G	15.0	27	1	0.18
EF-111	23.0	40	2	0.41
Total		2238	100	**29.53**

Bomber

Type	Cost	Number	% of Total	weightcost
B-52	7.3	136	54	3.96
B-1	215.0	95	38	81.37
B-2	500 **	20	8	39.84
Total		251	100	**125.2**

Cargo/Tnkr

Type	Cost	Number	% of Total	weightcost
C-130	5.2	277	25	1.31
C-141	20.0	243	22	4.43
C-5	100.0 *	82	7	7.47
C-17	300.0 **	120	11	32.82
KC-135	7.0	316	29	2.02
KC-10	47.9	59	5	2.58
Total		1027	100	**50.63**

Trainer

Type	Cost	Number	% of Total	weightcost
T-37	0.185	531	30	0.06
T-38	1.2	618	35	0.42
JPATS	10.0	600 *	34	3.43
Total		1749	100	**3.9**

* Estimate or average of the various models (C-130 A, H, U, etc.)

** Cost figure obtained from program personnel

*** Represents the number of LANTIRN capable F-16s, not how many are equipped with LANTIRN on a given day. The number of F-16C/Ds is then 725 total F-16s minus 226 Lantirn capable equals 499.

The historical CFIT mishap rates shown on Table IV-3 and Figure IV-1 can used to make an estimate of the expected number of mishaps in the future. The second to the last two rows of Table IV-3 presents the mean (average) and standard deviation of the CFIT mishap rates, respectively. Inspection of the fighter/attack and also the cargo/transport CFIT mishap rate plots in Figure IV-1 show that using their computed mean is probably not representative of their future CFIT mishap rate. Note the reduction in mishap rate with time. This probably reflects better pilot awareness or better ground collision warning systems than in previous years. However, it is doubtful the trend will continue to zero. To estimate a future CFIT mishap rate, first a linear regression algorithm/curve was applied to the data to obtain a "trend" for the year 1994 and the result is shown in the row labeled "Trend" and plotted in Figure IV-1. Comparing the computed trend value on Table IV-3 to the data in Figure IV-I shows that the computed trend value appears reasonable.

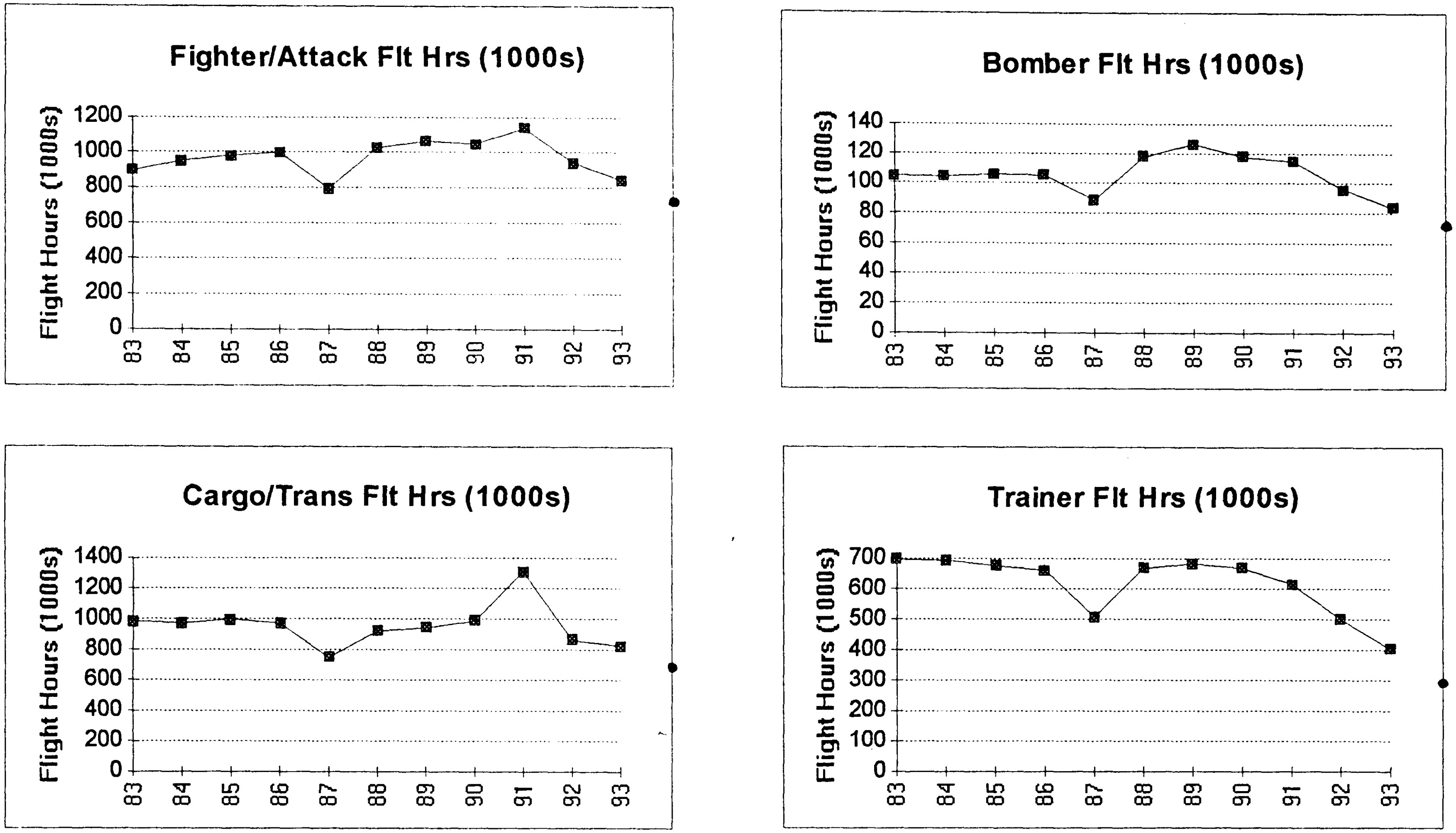
To estimate the CFIT mishap rate over the next ten years (from 1995 to 2005), this same trend value was held constant and assumed to represent the estimated future CFIT mishap rate. They are repeated here:

Table IV-5. Estimated Future Yearly CFIT Mishap Rate

Aircraft Class	Estimated Future CFIT Mishap Rate (per 100,000 hrs)
Fighter/Attack	0.56
Bomber	0.54
Cargo/Transprt	0.05
Trainer	0.10

Note that as expected, the fighter/attack class of aircraft have the highest expected CFIT mishap rate (this also hold true if the mean mishap values are used instead of a linear regression) and cargo/transport aircraft have the lowest (they don't fly close to the ground during typical missions nearly as often as other type aircraft - except they probably perform more takeoffs and landings per 100,000 flight hours).

Finally the estimated yearly future number of CFIT mishaps for any chosen type aircraft may be computed by multiplying the expected yearly number of flight hours for that aircraft times the expected CFIT mishap rate. Figure IV-2 presents plots of the historical flight hour data contained in Table IV-3. These data are then used to estimate the future yearly flight hours for each of the four aircraft classes.



Note: the data point in 1994 is actual data (not plotted so as to keep data consistent with mishap data which covers through 1993)

Figure IV-2. Flight Hours for Each Aircraft Class

Note the decreasing number of yearly flight hours since 1991, especially for the training class of aircraft. This is a reflection of the DoD draw-down. I would expect all four sets will continue their downward trend for another couple of years and then level off to a minimum level required to maintain readiness (unless of course a major conflict breaks-out which involves the USAF, in which case the curves will rise). Extending the yearly data presented in Figure IV-2 (including the 1994 data shown in Figure IV-2) and estimating the level-off value, gives the following values for the expected yearly number of flight hours: Fighter/Attack: 650,000 hours; Bomber: 60,000 hours; Cargo/Transport: 600,000 hours; and Trainer: 200,000 hours. The results are tabulated below:

Table IV-6. Predicted Yearly Flight Hours (average)

Aircraft Class	Future Estimated Yearly Flight Hours
Fighter/Attack	650,000
Bomber	60,000
Cargo/Transport	600,000
Trainer	200,000

The estimates in Table IV-6 are based upon a predicted yearly CFIT mishap rate. To estimate the total expected number of CFIT mishaps for a given type aircraft, the service life of the aircraft must be known. However, the analysis thus far has been performed on classes of aircraft, not unique types. As a result, the various aircraft service lives are distributed in the aircraft classes, thus diminishing the usefulness of the concept of a service life applied a class of aircraft (the service life for a class of aircraft is indefinite). Instead, the number of CFIT mishaps for each of the four classes of aircraft was calculated over four time horizons: 5, 10, 15, and 20 years. The results are shown in Table IV-7:

Table IV-7. Predicted Number of CFIT Mishaps, given a Time Horizon

	(/100K)				Time	Horizon	
Class	CFIT	Yearly	1	5	10	15	20
	Rate	Flt Hrs			Predicted	CFITs	
Ftr/Atck	0.56	650,000	3.6	18	36	55	73
Bomber	0.54	60,000	0.32	2	3	5	7
Cargo	0.05	600,000	0.3	2	3	5	6
Trainer	0.10	200,000	0.2	1	2	3	4

How much will the predicted CFIT mishaps shown in Table IV-7 cost the USAF? If the expected CFIT mishap aircraft were equipped with GCAS or GPWS, many of these mishaps could be prevented. As shown in Chapter II, not all of the mishaps could be prevented. An estimated 72% of them could be prevented if the aircraft were equipped with a GCAS (auto-recovery system) and similarly, 56% of them could be prevented if equipped with a GPWS (predictive, warning only)[28]. The answer to how much will CFIT mishaps cost the USAF is obtained by multiplying the expected number of CFIT mishaps by the estimated cost of the aircraft and the probability of preventing a mishap (0.72 for GCAS and 0.56 for GPWS). Thus, the average cost of each of the four classes of aircraft presented earlier in Table IV-4 is multiplied by the expected number of CFIT mishaps in Table IV-7, and then adjusted for prevention probability. The estimated cost to the USAF from these expected CFIT mishaps should be viewed as preventable costs. Table IV-8 below presents the estimated preventable cost for each of the two type of systems, GCAS and GPWS over the same four time horizons from Table IV-7.

Table IV-8. Estimated Total CFIT Mishap Preventable Costs

Class	Cost ($M) per a/c	**GPWS**	**Prevent**	**Cost ($M)**	
			Time	Horizon	(years)
		5	10	15	20
Ftr/Atck	29.5	297.7	595.4	909.6	1207.3
Bomber	125.2	140.2	210.3	350.5	490.7
Cargo	50.6	56.7	85.1	141.8	170.1
Trainer	3.9	2.2	4.4	6.6	8.8

Class	Cost ($M) per a/c	**GCAS**	**Prevent**	**Cost ($M)**	
			Time	Horizon	(years)
		5	10	15	20
Ftr/Atck	29.5	382.7	765.5	1169.5	1552.2
Bomber	125.2	180.2	270.4	450.6	630.9
Cargo	50.6	72.9	109.4	182.3	218.7
Trainer	3.9	2.8	5.6	8.4	11.3

The above table presents the predicted CFIT mishap costs which could be saved if the aircraft were equipped with either a GCAS or GPWS system. However, to equip the aircraft with either of these system requires expenses. Costs are incurred to develop

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[28] Estimates obtained from USAF Flight Safety office, HQ AFSA/SEFF, *Controlled Flight Into Terrain USAF History* briefing, Jan 94

the system hardware and software. Costs are incurred to test the system, to implement the hardware/software in the aircraft, etc. Each aircraft type (F-16, F-15, etc.) is unique and thus each aircraft type requires some degree of customization. For example, the data interface between a GCAS system and the avionics system on an F-16 is different than the interface on an F-15, even though both aircraft may use the same GCAS hardware (mega-DTC). In addition, each aircraft's flight control laws and flight dynamics are different, thus requiring different GCAS/GPWS mechanization. If there were a common GCAS/GPWS development among all the aircraft program offices, some of the development costs could be spread among them. Since this is not the case, each program office must pay the entire cost.

The cost to implement a GCAS or GPWS system is divided into two categories:
(1) Indirect/overhead, and (2) direct/per aircraft. These costs vary by aircraft program offices because each is unique, some more capable than others, and are difficult to precisely quantify[29] (in the same manner that it is difficult to exactly quantify the cost of a new aircraft). However, because much is known about the Mega-DTC and the associated GPWS system requirements (very similar to the successful AFTI F-16 system), cost estimates for the USAF in general to implement GPWS and GCAS systems into USAF aircraft will be computed using Mega-DTC associated costs[30]. The author acknowledges that these cost may not precisely represent the cost for a given aircraft modification/upgrade, but they do provide reasonable estimates which may be helpful. Table IV-9 presents the costs associated with GCAS and GPWS systems.

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[29] Cost figures for all the individual types of aircraft were unobtainable.

[30] Costs for the F-15E GPWS program were obtained and were close to those of the F-16 Mega-DTC effort.

Table IV-9. Cost to Development and Implement either GPWS or GCAS
(assuming existing sensors are adequate)

GPWS

Cost Type	Description of Requirement	Cost ($ M)
one-time*	Mega-DTC development with GPWS algorithm	10
Indirect	Flight Test	5
	Avionics Mod (for GPWS compatibility)	5
Direct	Mega-DTC hardware	0.03/aircraft
	wiring/aircraft mod	0.005/aircraft

\+ **GCAS** (in addition to above costs)

Indirect	Devlp. of Dig. Interface Card - Analog jets only	5
	OFP upgrade** - Digital jets only	10
Direct	DIC hardware - Analog jets only	0.04/aircraft
	wiring/aircraft mod	0.005/aircraft

* Note: the one-time cost is incurred only once because it is the cost to first develop the hardware which is common across the USAF.

** Cost figures for OFP upgrade is only for GCAS specific functions (i.e. assumed GCAS implementation to coincide with a planned OFP update release

Applying the cost figures from Table IV-9 to the USAF fleet shown in Figure IV-4 will provide an estimate to implement either GPWS or GCAS into the four class of aircraft. Table IV-10 presents the results.

Table IV-10. Total Cost to Implement GPWS or GCAS on USAF Fleet

The cost figures in the last three columns represent: **GPWS[GCAS]***

Type **Ftr/Attck**	No. of aircraft	Indirect (from	Direct Table IV-9)	Total
A-10	126	10[15]	4.4[10.1]	14.4[25.1]
F-16s (all)	725	10[20**]	25.4[29.0]	35.4[49.0]
F-15C/D	485	10[15]	17.0[38.8]	27.0[53.8]
F-15E	204	10[20**]	7.1[8.2]	17.1[28.2]
F-22	442	10[20**]	15.5[17.7]	25.5[37.7]
F-111	135	10[15]	4.7[10.8]	14.7[25.8]
F-117	54	10[15]	1.9[4.3]	11.9[19.3]
F-4G	27	10[15]	0.9[2.2]	10.9[17.2]
EF-111	40	10[15]	1.4[3.2]	11.4[18.2]
Total	2238	90[150]]	78.3[124.2]	**168[274.2]**
Bomber	No. of aircraft			
B-52	136	10[15]	4.8[10.9]	14.8[25.9]
B-1	95	10[15]	3.3[7.6]	13.3[22.6]
B-2	20	10[20**]	0.7[0.8]	10.7[20.8]
Total	251	30[50]	8.8[19.3]	**38.8[69.3]**
Cargo/Tnkr	No. of aircraft			
C-130	277	10[N/A]	9.7[N/A]	19.7[N/A]
C-141	243	10[N/A]	8.5[N/A]	18.5[N/A]
C-5	82	10[N/A]	2.9[N/A]	12.9[N/A]
C-17	120	10[N/A]	4.2[N/A]	14.2[N/A]
KC-135	316	10[N/A]	11.1[N/A]	21.1[N/A]
KC-10	59	10[N/A]	2.1[N/A]	12.1[N/A]
Total	1027	60[N/A]	38.4[N/A]	**98.4[N/A]**
Trainer	No. of aircraft			
T-37	531	10[N/A]	18.6[N/A]	28.6[N/A]
T-38	618	10[N/A]	21.6[N/A]	31.6[N/A]
JPATS	600	10[N/A]	21.0[N/A]	31.0[N/A]
Total	1749	30[N/A]	61.2[N/A]	**91.2[N/A]**

* The GCAS cost figure includes the GPWS cost - can't have GCAS without GPWS

** The additional $10M cost for GCAS is only the flight control OFP upgrade portion of the entire OFP upgrade (i.e. piggy-back GCAS onto planned OFP upgrade).

N/A: GCAS (auto-recovery) is probably Not Applicable to these type aircraft because their mission requirements do not warrant auto-recovery (a warning would suffice).

In addition to the Total costs shown in Table IV-10, the one-time cost of $10 million to develop the Mega-DTC should be taken into account. However, as the name implies, the one-time cost is included once, for the entire USAF, regardless of how many aircraft adopt the Mega-DTC. Similarly, if an aircraft program intends to use GPS as a navigational aid, then the cost of equipping the aircraft with GPS should also be taken into account.

As discussed previously, the cost figures in Table IV-10 are representative costs to implement GPWS or GCAS using the Mega-DTC upgrade as the baseline. This assumption is not valid for those aircraft not presently outfitted with the standard DTC hardware. Many the fighters/attack aircraft and the bomber aircraft shown in Table IV-10 are currently equipped with standard DTCs, and if not, the cost for a GPWS or GCAS system was estimated to be the same as that with a DTC. With the exception of the C-17, few or none of the cargo/transport and trainer aircraft are presently equipped with DTC hardware (the training aircraft are not even equipped with radar altimeters or GPS). However, for the purposes of this exercise, the cost to develop a new, relatively simple GPWS upgrade which would achieve Mega-DTC capability from those that are presently installed was assumed to be the same as that with DTC-equipped aircraft.

What conclusions can be gathered from Table IV-10? First, and most obvious, GCAS is always more expensive than GPWS because GCAS requires an additional modification to the aircraft flight control systems. For digital aircraft (F-16, F-15E, F-22, C-17, and B-2), the OFP software is upgraded throughout the fleet, not on a per aircraft basis (the significant cost is in developing the new software). However, to install GCAS on an analog aircraft requires that each aircraft's digital-to-analog card (Digital Interface Card) be modified ($20k per card times two cards per aircraft is how the $0.04 million cost figure was derived on Table IV-9). Therefore, the second conclusion to be gathered from Table IV-10 is: for every analog controlled aircraft, the total cost of a GCAS (auto-recovery) is approximately double the total cost of a GPWS (the $40K is required for each individual aircraft). Lastly, an most importantly, how do the cost figures in table IV-10 compare to the estimated total preventable cost figures in Table IV-9?

The easiest way to compare the cost of equipping aircraft with GPWS or GCAS to the preventable CFIT mishap cost is to place the figures side by side. Table IV-11 does just that. Note that the one-time cost to develop the Mega-DTC is included once in the fighter/attack aircraft class because they are the ones who paid for its development.

Table IV-11. Comparison of GPWS/GCAS Cost to Preventable CFIT Mishap Cost

		GPWS	Prevent	Cost ($M)	
	GPWS		Time	Horizon	(years)
Class	Cost ($M)	5	10	15	20
Ftr/Atck	178.3 *	297.7	595.4	909.6	1207.3
Bomber	38.8	140.2	210.3	350.5	490.7
Cargo	95.9	56.7	85.1	141.8	170.1
Trainer	91.2	2.2	4.4	6.6	8.8

		GCAS	Prevent	Cost ($M)	
	GCAS		Time	Horizon	(years)
Class	Cost ($M)	5	10	15	20
Ftr/Atck	284.2 *	382.7	765.5	1169.5	1552.2
Bomber	69.3	180.2	270.4	450.6	630.9
Cargo	N/A	72.9	109.4	182.3	218.7
Trainer	N/A	2.8	5.6	8.4	11.3

* Includes one-time $10 million cost to develop the Mega-DTC

Table IV-11 shows that it is certainly cost effective and feasible to equip fighter/attack aircraft and bombers with either GPWS or GCAS because the cost to equip them is well below the preventable CFIT costs, regardless of the time horizon. The data also shows that equipping cargo/transport aircraft with GPWS is not cost effective until between 10 and 15 years after adoption, based upon the computed "weighted average" cost. This average cost however, was weighted significantly with older, cheaper aircraft such as the KC-135 and C-141. Therefore it is not cost effective to equip this old aircraft with an expensive new GPWS, but it is cost effective to equip new aircraft such as the C-17 with such as system. It is not cost effective to equip training aircraft with GPWS (nor GCAS). As will be explained in the summary section of this chapter, although the above table may not as accurately as possible reflect the true GPWS/GCAS and preventable costs for each individual type of aircraft, they nonetheless are useful as a "litmus test". As will be explained in the summary section, the preventable cost figures are conservative (underestimates), thus making the benefits of GPWS/GCAS on fighter/attack aircraft and bombers even more obvious (though GPWS/GCAS may not be advantageous on some low priced aircraft such as the A-10).

These data merely account for the monetary cost of losing an aircraft. As discussed in Chapter I, lives are lost as a result of CFIT mishaps. Based on that fact alone, it may seem reasonable to equip aircraft with GPWS/GCAS systems which wouldn't normally be equipped with them as determined by similar costing methodologies.

Break-even Analysis

Another way to look at the cost benefit/feasibility of GPWS or GCAS systems would be to ask two related questions: First, assuming the GPWS and GCAS costs shown in Table IV-11 and then assuming cost of aircraft, how many CFIT mishaps (or years) are required for the cost of implementing GPWS/GCAS to break-even with the CFIT mishap costs? Second, for a range of aircraft costs, what is the required GPWS/GCAS cost to break-even at each of the four time horizons?

To perform the first analysis, Table IV-12 presents the cost figures used in the analysis. Once again, the probability of a GPWS or GCAS preventing a mishap is accounted for in the analysis (72% of CFIT mishaps are preventable with GCAS and 56% for GPWS).

Table IV-12. Number of CFIT Mishaps to Break-even

Class	Aircraft Cost ($ M)	GPWS Cost ($ M)	GCAS Cost ($ M)	# of CFITs for GPWS to brkeven	# of CFITs for GCAS to brkeven
Ftr/Atck	29.53	178.3	284.2	10.8	13.4
Bomber	125.2	38.8	69.3	0.55	0.8
Cargo	50.6	95.9	N/A	3.4	
Trainer	3.9	91.2	N/A	41.7	

Combining this with the yearly flight hour estimates and CFIT mishap rates in Table IV-7 yields the number of years required to break-even.

Table IV-13. Number of Years Required to Break-even

Class	GPWS - years	GCAS - years
Ftr/Atck	3.0	3.7
Bomber	1.7	2.4
Cargo	11.3	
Trainer	208.7	

To perform the second break-even analysis (compute GPWS/GCAS cost to break-even with preventable CFIT mishap cost), an equation was derived which describes the relationship between aircraft cost and the resulting necessary GPWS/GCAS cost to break-even at a specified time horizon. The mishap rates and yearly flying rates calculated previously (shown in Table IV-7) are used in the computations.

The equation is:

Equation IV-1: $S = (\text{Time Horizon}) * M * P * C$

where S ($ millions) = cost of either GPWS or GCAS in order to break-even at the time horizon (in years). Note: the cost includes flight test, development costs, etc.

M = number of likely CFIT mishaps in one year obtained from 1-year time horizon data in Table IV-7.

P = probability that either GPWS or GCAS will prevent a mishap. P= 0.56 for GPWS and 0.72 for GCAS

C ($ millions) = Cost of each aircraft

As an example, suppose we use the data from Tables IV-12 and IV-13 for a cargo/transport aircraft which is planning to install a GPWS system. If time horizon = 11.3 years and the aircraft costs $50.6 million, then the break-even cost for the GPWS is $95.9 million (which matches the GPWS Cost data point in Table IV-11).

Cost Analysis Summary

The preceding cost analysis section used a straightforward methodology to ascertain the cost effectiveness of GPWS and GCAS systems. Using the probability of CFIT mishaps (mishap rate per flight hour), together with the predicted number of flying hours for various class of aircraft, the likely number of future CFIT mishaps can be estimated. The preventable CFIT mishap cost is then calculated by multiplying the likelihood a GPWS/GCAS system will prevent a mishap by the cost of CFIT mishaps (based on cost of various mishap aircraft). Finally, this preventable CFIT mishap cost is compared to the cost to equip these aircraft with either GPWS or GCAS.

To simplify the analysis for this paper, the described cost methodology was applied to aircraft delineated by four distinct classes: aircraft/fighter, bomber, cargo/transport, and trainer. CFIT mishap data specific to aircraft type were not obtained for this paper. Helicopters were excluded because of their unique missions and GPWS/GCAS requirements.

It is important to remind the reader that the preventable CFIT cost figures presented in Table IV-11 for the four classes of aircraft were derived using weighted averages of aircraft costs from aircraft within each class. As Table IV-4 shows, the cost of some fighter/attack aircraft, as well as a B-52 bomber, are well below the average cost of aircraft in that class (for example, an A-10 cost $5.3M, yet the average cost for a fighter/attack class aircraft is $29.5M). As a result, the cost comparisons in Table IV-11 on those aircraft that have significantly different costs from the average, may not accurately portray GPWS/GCAS cost benefits. However, in general, the analysis performed in this paper does highlight the overall cost benefits of GPWS/GCAS systems.

It is also important to remind the reader that, in general, the cost figures used to price the various types of aircraft are conservative estimates. Since these cost figures were then used to calculate the likely future preventable CFIT mishap costs shown in Table IV-11, they too are conservative. They are conservative because the weighted average aircraft cost for each class of aircraft included older, cheaper aircraft which will phased out over time and replaced by much more expensive aircraft. In addition, the cost figures for the various aircraft are costs for baseline aircraft and do not include likely avionics upgrades made to them in the future. Also, the computed CFIT "trend" and estimated future flying rates were derived from recent data (years 1993 - 1994) which exhibit substantial declines in flying activity. Though this decline may continue and then stabilize at a level below 1995 values (the "trend" value), it is also possible that the USAF will be asked to support at least one conflict in the next 10 to 20 years which will raise the flying rate (to what level is unknown, but probably above the estimated values used in this paper). Lastly, the cost to train the aircrew killed in the CFIT mishaps was not included in the preventative CFIT mishap cost data (I wanted to keep the cost figures as conservative as possible to not overestimate the GPWS/GCAS benefits). However, using a conservative training cost of $1 million per pilot and assuming every CFIT mishap is fatal (a reasonable assumption), the number of likely future CFIT mishaps shown in Table IV-7 represent the additional CFIT mishap cost (in million of dollars) to be added to the preventable costs in Table IV-11 (for example, 18 CFIT mishaps likely within a five year time span as shown in Table IV-7 means an additional $18 million should be added to the $297.7 million GPWS preventable cost shown in Table IV-11).

The same methodology employed in this paper on aircraft classes could just as well be applied on all the specific types of aircraft (F-16, F-15, etc.). For instance, an F-16 program manager could use F-16 CFIT mishap data, F-16 aircraft pricing, and GPWS or GCAS acquisition costs specific to the F-16, apply the cost methodology employed on the various class of aircraft, and more accurately determine cost effectiveness. However, if a similar question were asked about a new aircraft, one without a large flight hour sample time (thus unrealistic CFIT mishap rate), then the overall fighter/attack mishap rate calculated in this paper could be used in conjunction with actual F-22 cost figures.

The preceding cost analysis clearly shows that implementing either a GPWS or GCAS system on fighter/attack aircraft and bombers is cost effective by a very wide margin. If such systems are so cost effective, why hasn't the USAF installed them. The next chapter of this paper will explore reasons why the USAF has been slow to adopt these systems to date and re-examine the current initiatives underway to do so.

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V. RESISTANCE TO ADOPTION OF GCAS

Until very recently, with the exception of the new Mega DTC acquisition initiative and the yet to be built F-22, no strong effort has been made to employ GCAS on current USAF aircraft. To date, no USAF aircraft is equipped with an auto-recovery GCAS. The cost analysis in the previous chapter clearly highlights the beneficial economics of the USAF adopting such systems, the system descriptions in Chapter III described GCAS feasibility, and Chapter II described the loss of lives and aircraft as a result of controlled flight into terrain. The numbers and the statistics clearly show the advantages outweigh the disadvantages. There are a variety of factors as to why the USAF has been slow to adopt GCAS. These factors may be considered within two categories: the psychological/human-oriented factors, and the financial/institutional factors. Literature and studies have shown that both psychological and institutional factors can be potentially significant in the manufacturing sector where the adoption of a new technology can affect blue-collar workers through layoffs, job re-orientation, etc. Although the USAF is not the manufacturing sector, nonetheless, the framework used for studying the effects of adopting new technology in the manufacturing sector can be used as a tool for understanding possible reasons for resistance to adoption of GCAS technology in the USAF.

Psychological Factors

Adopting new technology, as with any kind of change, affects people psychologically by altering their work habits. The implications of the job alteration can be positive or negative and may involve perceptions as well as realities[31]. On the positive side, the psychological implications of adopting new technologies include: challenges and commitment. On the negative side, implications include: stress, threat, uncertainty, and conflict. Clearly, each of these factors are subjective and can vary greatly from person to person. Some individuals thrive on challenges, while others strongly resist changes. Data suggest that individuals who are compliant, dependent, and risk-averse will have difficulty in circumstances where the nature of technological change is revolutionary. Conversely, while such workers may have an easier time with evolutionary change, slow change is likely to be frustrating to persons who are more aggressive, autonomous, and change-seeking. This raises an interesting dichotomy within the USAF with respect to GCAS technology adoption. Clearly the USAF is and has always been heavily reliant upon technology to perform its mission. Technology adoption is a common occurrence for the USAF. Moreover, while the majority of USAF flying personnel could easily be categorized as aggressive and autonomous, they can also be quite resistant to change - including technological change. With very few exceptions, pilots and most other USAF personnel are willing to adopt new technology

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[31] Hamid Noori, *Managing the Dynamics of New Technology*, Prentice Hall Press, 1990, pages 272-278.

in their aircraft because the combat capability of the aircraft is enhanced. Although they are certainly risk-accepting when it comes to the performance of their duties, pilots and career officers tend to be risk averse regarding major changes or making decisions which may have a long-term affect on their career. Therefore, the reason for GCAS resistance is probably because it is viewed as a revolutionary change, a high safety- and technology-risk (above risk-adverse thresholds), and as having a possible direct impact on mission performance.

The following are psychological-related factors for the resistance to GCAS adoption beginning with possible mission impact. First, many pilots believe that GCAS type systems deter from their ability to push the aircraft and him/herself right to the edge, as is required in many of today's combat environment. Developing and honing superior piloting skills requires pushing the man and machine right to the edge. Some believe, based upon experiences with earlier GCAS/GPWS technology or upon limited experience, that GCAS type systems actually prevent the pilot from pushing the aircraft and themselves to the edge. They may not realize that a properly designed, robust predictive GCAS, such as that on AFTI, will actually allow them to push the aircraft literally right to the edge and protect them in the event they are distracted or not aware of the danger. Secondly, The systems must not be a nuisance. The must not unnecessarily warn or distract the already saturated pilot. The key word is "unnecessarily". How does the GPWS/GCAS know whether the pilot is aware of a possible collision and not activate when the pilot is aware of the danger and yet, activate if he/she doesn't? Lastly, they may be uncomfortable or distrust GCAS because of their experiences with unreliable, un-robust computer/software systems of past. Many first generation systems which these General Officer pilots used in combat or training were prone to nuisance errors, which then severely detracted from the aircrew's trust of the system. The same is true for today's younger pilots, but on new systems not previously in existence. Pilots and senior management must believe that now the engineers can design and develop a reliable system which must work and with little or no nuisance errors. Now they are being asked to actually allow *the aircraft* to avoid terrain while their attention is focused elsewhere (during TF/TA, the aircrew monitors the TF/TA displays and system very closely).

Degraded Mission Performance

Technological innovation and human skills sometimes clash. There is no question that the human brain's ability to quickly assess a situation and adapt to a rapidly changing environment, as in air combat, gives it advantages over a computer and software. Technology is marvelous at supplementing human skill. The problem arises when the human perceives that too much must be relinquished to the computer. Today's pilots are highly educated (some hold advanced degrees), aggressive, motivated, and well trained individuals. They also tend to be very competitive, which is crucial in air combat and probably more so in fighter/attack pilots. In an effort to be "a better stick" than the next person, pilots tend to fly the aircraft and themselves to the edge of the envelope. To develop this "edge", they must train and develop piloting skills in dangerous and sometimes unforgiving environments using aggressive and stressful tactics. Sometimes they exceed either their ability, or the performance design of the aircraft, and the result is a CFIT mishap. Taking this into account means that pilots are wary of relinquishing a task that they feel they can do better (because it gives them an advantage over their foe). In some instances, the pilot's ego comes into the picture. Fighter pilots can be especially wary of GCAS type systems. "Take control away from me? No way".

Since pilots are likely to use GCAS in a myriad of circumstances, such as, low-level maneuvering, dive bombing, strafing, and TF/TA, GCAS systems must be robust and reliable in a variety of circumstances. A GPWS that works well under only one condition, but not in others, could be either dangerous or unsatisfactory. It might be called upon to work in a situation it was not designed for. Pilots will always "press the boundaries of the envelope" and so a GCAS system must be both reliable and robust. For instance, a GCAS designed for distraction warning during TF/TA may actually inhibit the aircraft from performing a different task such as low altitude strafing. The pilot will know that the aircraft is inhibiting his performance and will either turn the system off completely (if possible), or insist that it be improved or removed. Anything which prevents him/her from attaining the highest level of piloting proficiency during peacetime training will be resisted because their life will depend on it during wartime.

Technology and Safety Risks

In order to be widely accepted and adopted by the USAF, GCAS and predictive GPWS systems must have very few, if any, nuisance errors. The systems must also be robust in their design parameters and yet not too narrowly constrained (i.e. only work against flat earth, or in level upright flight, etc.). Often, their function directly conflicts with what the aircrew is trying to do, especially if the GPWS tries to warn too far in advance (this happens when the system must estimate or extrapolate terrain slope and altitude). These two factors are closely related and have been critical in the slow adoption of GCAS and predictive GPWS. Solving these two problems is not easy, as evident by the many past failures to develop and field a system deemed "adequate" by aircrews.

Is it feasible to develop a reliable system? As the AFTI F-16 test pilots state: "a reliable, nuisance free system is the only acceptable option for the user." The AFTI GCAS computations are the best yet and have been demonstrated inflight. As described in the GCAS/GPWS Initiatives portion of Chapter III, disjointed efforts within the various fighter/attack System Program Offices to develop a predictive GPWS/GCAS have not been very successful. Some were designed for a very specific purpose (in the case of the F-15E, it was to warn a distracted or fixated pilot of an imminent ground collision) and attempted to be used for purposes greater than designed for (during combat descents). It warned the pilot when a warning was unnecessary because he already had complete situation awareness. As a result, aircrews felt distrustful of the system or claimed it was nuisance prone and unsatisfactory. Until word can get out about the success of AFTI GCAS and spread throughout the operational forces, pilots will remain resistant to GCAS adoption on "their" jet.

Until the recent generation, pilots and aircrew of the past tended not to trust computers and avionics to take control of the aircraft for them, as would be the case for an auto-recovery GCAS. Beginning with a small number of Lieutenant Colonels, more Majors, and many Captains and below, the recent generation of pilots have grown very accustomed to computers and avionics. Although they may be skeptical (a healthy thing for a pilot), pilots of today already rely a great deal on computers and avionics to perform nearly all tasks. The United States military has always pursued the doctrine of relying upon technology in order to minimize loss of life: that is, our aircraft, tanks, ships, etc. shall be more advanced than our foes. We will not rely upon numbers to win a war, we will rely upon the ingenuity of our people by giving them the most advanced weapons feasible and letting them use that technology to protect our country. This doctrine promotes the use of high technology in our aircraft. However, with each major advancement in technology there is the potential for a natural human reluctance to adapt to change. Distrust emerges from civilian critics, from military critics, pilots, maintenance personnel, logistics, engineers, among others. There is distrust of the high technology system itself and distrust of how it will be used. Although nearly all of today's modern aircraft are fly-by-wire (especially fighter/attack aircraft which are built inherently unstable for maneuverability and weight reasons), today's pilots do not yet trust systems that take control of the aircraft away from them. This is especially true for fighter pilots. Pilots who routinely fly auto TF/TA missions, however, are likely to be more comfortable with adopting GCAS, including those fighter pilots who have performed TF/TA. During auto TF/TA, the aircraft and its systems *are* flying the aircraft and avoiding the ground. However, the pilot and aircrew constantly monitor the system and displays to ensure the system's health and performance and take control if they see something of concern (a canopy full of earth).

Pilots have always been willing to shed secondary/distractionary tasks into the hands of computers and let the "real flying" go to the pilot. First came autopilots. This system is common in nearly every aircraft built today, both military and civilian. Next came adoption of radar and other electronic warfare equipment which took air combat away from the limits of human eyesight to another longer-range medium. At about the same time as the introduction of high technology avionics/weapons, pilots were encouraged to trust TF/TA systems during low altitude missions. Initially these systems could only supplement the pilot manually flying the aircraft, but today TF/TA is near autonomous. Lastly, the latest major leap in aircraft technology advances came with the F-16 and its first of a kind *analog* fly-by-wire flight control system. Now not only are *digital* computers and software performing a supporting role, but they are now actually "flying" the aircraft. They make minor corrections automatically in today's inherently aerodynamically unstable/marginally stable aircraft (to enhance maneuvering performance and reduce weight) to keep the aircraft from tumbling out of the pilot's control. A GCAS type system however, is asking the pilot to allow a computer to take control of the aircraft away from the pilot in the event he/she "screws up" as ascertained by the same computer which is taking control. That goes against the grain of what many good pilots feels and believes is their job. Not only that, but in the case of a DTED based GCAS they are being asked to trust a computer and system which has no direct sense of the terrain (remember these systems do not rely on radar to sense the terrain).

The psychological factors that contribute to the resistance of adopting new technology can be considered at two levels: employee (line pilots, engineers, and commanders) and management (system program managers and upper echelon/headquarters personnel). The resistance factors within each of the two levels overlap. What may be a factor to the front-line pilot may also be a factor to a general in the Pentagon. To make GCAS adoption both possible and faster requires embracement of the technology from both levels of personnel. Clearly the senior USAF officers and program managers (SPO directors) have the decision authority, but the acceptance and pull comes from the line pilots and maintenance personnel. Besides overlaps between employees and management, management overlaps greatly with the second factors in slow adoption of GCAS: institutional and financial factors.

Financial and Institutional Factors

The authority to make decisions regarding GCAS rests with three organizations: Headquarters (HQ)-Pentagon; the Commanders of the combat operational commands (primarily Air Combat Command-ACC and Air Mobility Command-AMC), and the various System Program Offices (SPOs) located at Wright-Patterson AFB who manage the actual development and acquisition of new and existing aircraft systems. The DoD weapon system acquisition methodology is extremely complex and beyond the scope of this paper. In simple terms, any effort to install GCAS (or any such major system on new or existing USAF aircraft) would require the above three groups' mutual concurrence beginning with the user: the operational commands. The operational command(s) must document the requirement for such a feature and have the Operational Requirements Document (the ORD) approved by HQ and the Office of the Secretary of Defense (OSD). Next, the ORD is then used by the SPOs to write System Specifications for contractors to build the equipment. Contractors are selected from proposals sent following the SPO's request for bids. Only after a lengthy design, development, and test process involving Congress, HQ, OSD, and many others over the span of years, can the system finally be fielded back to the user(s) who originally requested it.

When the above DoD acquisition process and politics is combined with personal and tight financial constraints that exist today, it becomes clear why GCAS is not yet installed on USAF aircraft, despite its enormous and potential benefits. It is only within the last decade that USAF senior management placed the necessary emphasis on GCAS and much improved GPWS systems to get the ball rolling. It is now up to the younger, mid-level managers to make GCAS an operational reality.

Fiscal Resistance

The following are budgetary factors for the slow adoption of GCAS technology. The DoD budget, though very large (approximately $280 billion in fiscal 1994), is finite. All three services have their own ideas for how to best spend defense dollars and they actively compete for the DoD resources. Within the USAF, all of the various programs (not just aircraft programs) submit requests for money and therefore, also compete within the USAF budget. Since the mission of the USAF, like all the armed services, is to defend the US, the tendency is to spend limited resources on those items that directly aid in the defense of the country. That means systems which are used during wartime are given the highest priority. Since GCAS is most useful during peacetime training, it is placed further "down the list" than a new weapon. The fault with that logic however, is that the defense preparedness is degraded every time an aircraft is lost to a mishap because after the mishap there will be fewer aircraft. However, in many people's minds, the benefit of GCAS is secondary or indirect because it does not directly help with air combat/warfighting.

During the 1980s when DoD spending was growing rapidly, it would have been easier to adopt GCAS. However, at that time the GCAS/predictive GPWS systems were inadequate and very prone to nuisance errors, thus were not placed on USAF aircraft. Also, Digital Terrain Data was a new technology and not available on many aircraft (it still isn't, but the Mega-DTC effort is a move to remedy the situation). The AFTI F-16 did not develop and test their GCAS system until the 1990s. With the end to the Cold War, comes budget reductions. On the one hand, because the budget is reduced, competition for money is increased and it becomes more important to justify every spending item - including GCAS. On the other hand, because we can afford less aircraft (the price of each continues to escalate at the same time when the budget is falling), it becomes more important to save aircraft and not let them become CFIT mishaps. As a result, it may be easier to justify the need for GCAS today than say, 10 years ago.

Acquisition Process Resistance

A second budgetary/institutional issue affecting the adoption of GCAS is the DoD acquisition process itself. The acquisition process is extremely complex and slow. The budgets that are submitted each year are projected years into the future, and each year, they are subject to revision by OSD, Congress, and the President. The inertia in such a process is enormous. That is not to say progress is impossible. Obviously, the process *does* work, as evidenced by the superior aircraft sitting on USAF base ramps around the world. For GCAS to be installed in aircraft, the user commands (ACC, AMC, etc.) must include the funding request in the Program Objective Memorandum (POM) and the requirements must be included in the program's Operational Requirements Document (ORD). Since the POMs and ORDs are reviewed by the Air Force senior staff, the upper echelons must agree with what is requested. Even though line pilots may want a GCAS, unless the commanders agree, GCAS will not move forward. Fortunately, digital computer technology has advanced to a point that GCAS is now much more affordable and practical, at a time when the commanders are beginning to embrace its need.

Unfocused Effort

Lastly, the overall GCAS/GPWS effort is unfocused across the USAF. Each aircraft SPO must budget for their specific GCAS/GPWS. They must individually pay for the development, the testing, and the fielding costs. If a common GCAS/GPWS could be developed for the USAF, costs could be reduced. Exploiting economy of scale and system commonality, development, logistics, and maintenance costs could reduced. Although some elements of hardware and software would need to be customized for specific aircraft (mainly in the I/O interfaces), most of a USAF-wide GCAS/GPWS could be a common effort. As discussed in Chapter III, a common DTED platform and trajectory/terrain prediction algorithm could be used across the fleet (the Mega-DTC is exactly that). However, each aircraft would require unique ground and flight test to ensure acceptable operation. Most likely, an update to the avionics Operational Flight Program (OFP) would be necessary for display/HUD symbology or aural warning. Additionally, if a GCAS is utilized, each type aircraft would require its unique OFP modification in order to tie the GCAS recovery to the aircraft's flight control system.

Strategy for Change

Textbooks discuss various strategies to be employed which best resolve problems which involve resistance to change and technology adoption. As before however, the literature is primarily aimed towards manufacturing processes and technology implementations. Nonetheless, the strategies do provide a framework with which to discuss the USAF adoption of GCAS technology.

One of the contributors to technology adoption and change resistance are the people involved. This was discussed at some length previously. What was not discussed was the personality types typically encountered in organizations. Personality plays a role in how, and at what pace change will be accepted by individuals. Table V-1 provides a typology of personalities found in organizations[32].

Table V-1. Organizational Personality Types

Promoters	Inhibitors
Participants- people who recognize their responsibility to the success of the project.	Spectators- people content with the usual route and are unimpressed with "new" ways.
Movers- people who remove obstacles when they "bump" into them.	Protectors- people who are concerned with their "kingdoms" and the anticipated loss thereof.
Shakers- people who recognize an opportunity and will make it happen.	Doubters- people who are unsure of the adaptation of the new system in their "unique" mission.
	Worriers- people who are afraid of the hardware and ignorant of the software.
	Switchers- people who delegate their own responsibilities.

Like most organizations, the USAF strives to encourage those people who are the promoters (see Table V-1). In general, the majority of the USAF leaders and pilots are promoters and as a result, are usually more readily willing to adopt new technology. But because of career concerns, individuals may be less willing to make changes unless they know they are not alone in their views. Perhaps more significantly, they do not gain financially as a result of adopting change as would probably be the case in private industry and business (through gain sharing or bonus).

Leonard-Barton and Krause [1985] use the term "hedgers" to describe risk-averse managers who refuse to take a stand (either for or against) the adoption of new technology until they receive signals telling them which way to go. Implementation of new technology can be successful by ensuring that the hedgers are on the organization's side before the process begins. The key figures in implementing GCAS technologies who may hedge are the aircraft system program office managers and the various operational wing commanders. To strongly get behind GCAS initiatives, they must be signaled (through policy memos from above or from overwhelming support by their subordinates) that the USAF as a whole is fully behind the change and they must also have a strong operational interest in the objective the technology is to provide (such as enhanced safety) before they too will fully support the change. That is not to say that these managers would disregard the wishes of their superiors or that all are risk averse. However, it is crucial that system program office directors and wing commanders

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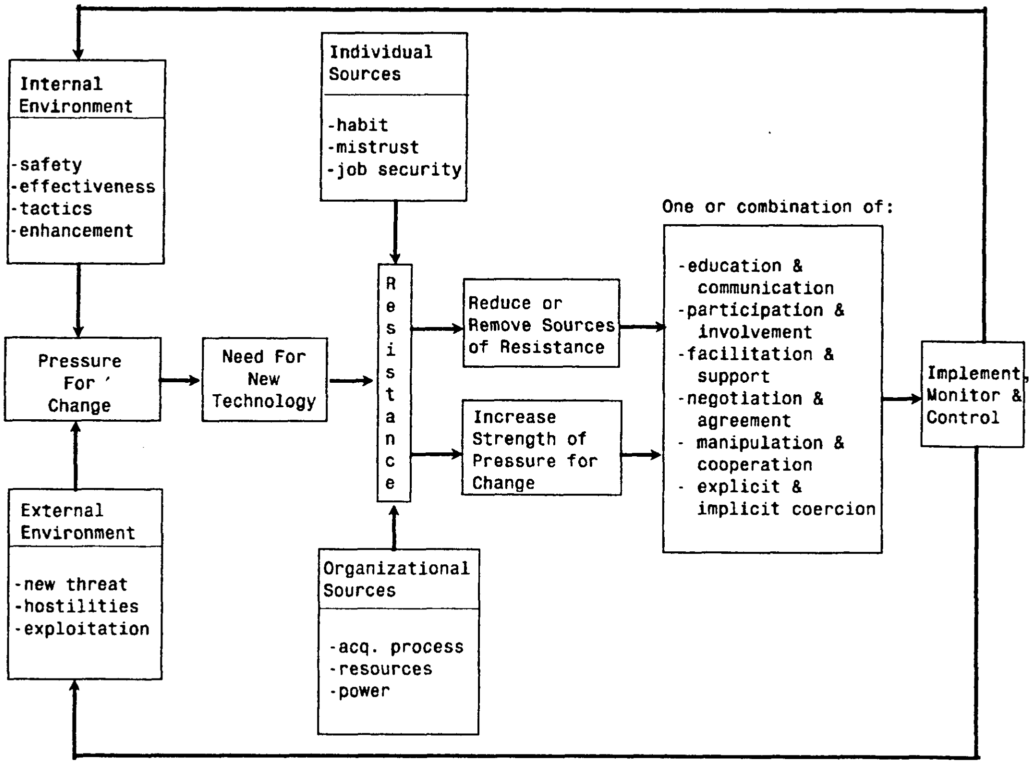
[32] Hamid Noori, *Managing the Dynamics of New Technology*, Prentice Hall Press, 1990, page 274.

embrace the change, and then lead the effort both for their superiors and to their subordinates (the line pilots and squadron commanders).

Given the resistance to GCAS adoption previously discussed, what should be the strategy employed by the USAF to smoothly and more quickly adopt GCAS? Figure V-1 presents a diagram of some of the various sources of pressure for change, the sources of resistance to change, and how to deal with them in implementing a new technology successfully[33]. The figure is intended to be representative, not all inclusive.

Figure V-1. Implementing Technology Change within USAF



In general, literature supports the hypothesis that nonparticipative methods of implementing new technologies are very risky. In the case of the USAF and GCAS, achieving "buy-in" by the operational pilots is very much possible, and thus a participatory strategy should be employed.

Inlight of the USAF organizational hierarchy, the predominate promoter personality traits exhibited by many managers, and the nature of the resistance (perceived reduction in mission capability and distrust of GCAS system), the best strategy to implement GCAS technology is two-fold. First, make system program managers (SPO directors) and upper echelon management aware of the latest advances in GCAS technology and have them promote the adoption of GCAS technology to the

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[33] Hamid Noori, *Managing the Dynamics of New Technology*, Prentice Hall Press, 1990, page 275.

forces. Second, educate aircrews and flight-line level personnel through journal articles or by word of mouth regarding the latest technology advances in GCAS technology to ease the adoption process. Aircrews are less likely to get "in line" unless they are convinced by their peers that the new technology is something good and not just a decree from above. The keys to the success of a viable GCAS lies with resolving the nuisance error problem, system repeatability, and no degradation of mission performance. The AFTI F-16 GCAS demonstrates a viable, repeatable system without using GPS navigational updating that many of today's [and tomorrow's] aircraft are[will be] equipped with.

The strategy employed today is a slow moving participatory movement within each of the various aircraft program offices. They are aware of the CFIT problem and that senior management would like to have the numbers reduced. In response, the individual SPOs study the problem, submit a Request For Proposals, and task the contractors to develop a GPWS/GCAS system. In many cases the SPOs may not be aware of problems encountered by other SPOs who have developed/studied the problem previously, nor are aware of AFTI implementation (such was the case for the F-15E). These factors, combined with the enormous inertia and timeframe involve in the DoD acquisition process, make for slow adoption of GCAS technology. An important factor in implementing the proposed two-fold strategy and picking up the pace of GCAS technology adoption is an organized, common focused GCAS/GPWS system development effort undertaken by one office (probably SAF/AQ) within the USAF instead of the independent development efforts undertaken by the individual system program offices.

VI. CONCLUSIONS AND RECOMMENDATIONS

The Problem

The estimated cost to the USAF as a result of 172 Controlled Flight Into Terrain (CFIT)-caused Class A-destroyed aircraft mishaps from 1980 to 1993 was nearly $1.5 billion in lost aircraft and 176 fatalities. The overwhelming majority (70%) of all CFIT mishaps (not just Class A, but B, C, and HAP) involve fighter/attack type aircraft. They tend to fly low-level more often than other aircraft and maneuver more rapidly, thus increasing the susceptibility to pilot distractions, g-induced loss of consciousness (GLOC), etc. Not surprisingly, the majority of all CFIT mishaps occur in daytime (more missions during that time) and a large percentage (40%) involve pilots with less than 500 hours in the mishap aircraft type. However, CFIT can also happen to very experienced pilots as well. Thirteen of CFIT crews had over 4000 hours flying experience and one had over 4000 hours of time-in-type.

The factors which lead to 12.6 CFIT destroyed-aircraft mishaps each year are: the environment (day, night, weather, etc.), aircrew experience, aircraft type, and human factors (GLOC, disorientation, etc.). Human factors play a major role in CFIT mishaps. The aircrew may be distracted, take attention away from avoiding the ground, and collide with it. Also, the pilot may GLOC (a suspected factor in 9% of the CFIT mishaps) or become spatially disoriented (a suspected factor in 19% of the CFIT mishaps).

Efforts to Fix the Problem

To help aircrew avoid collisions with the ground, Ground Proximity Warning Systems (GPWS) were developed approximately ten years ago and installed on a few aircraft (primarily on fighter/attack aircraft). However, as demonstrated by the CFIT statistics, these GPWS are inadequate. If at all, they perform cursory aircraft trajectory predictions and highly simplified predictions of the terrain (usually obtained from the radar altimeter which has extremely limited forward vision). Some rely only on current sensor inputs with little or no predictive capability. Once system parameters are exceeded, a aural or visual (as a "break X" on the Heads-Up-Display (HUD) or other display) warning is given to the crew. Virtually all of today's GPWS systems suffer from nuisance faults (unnecessary or false warnings) and therefore, are not "trusted" by the pilots. They either turn them off (if possible) or on occasion, ignore the warnings. The problem is, sometimes the unheeded warning is valid, or too late.

During the past five to six years, numerous aircraft System Program Offices have developed improvements to their current GPWS system, but few were satisfactory enough to install on the operational fleet or solve the CFIT problem. It is a difficult problem to solve because there is a complex tradeoff between ample warning and nuisance errors. The system must always operate when needed, but not give a warning when not needed.

The current effort to develop an improved GPWS is disjointed across the USAF without a common system design. However, a significant advancement to the CFIT problem was made in the late 80s/early 90s on the experimental Advanced Fighter Technology Integration (AFTI) F-16 aircraft. This test program developed a robust, relatively simple Ground Collision Avoidance System (GCAS) which is an auto-recovery (pilot hands-off) GPWS. The AFTI GCAS uses an onboard stored digital map (40,000 sq mi of terrain) in conjunction with a radar altimeter-updated INS to predict the upcoming terrain without really "seeing" it. The Digital Terrain Elevation Data (DTED) is stored and loaded from a modified Digital Transfer Cartridge (DTC) found on many aircraft in the USAF inventory. The 1992-93 test results were so encouraging that it's software algorithm was adopted on an upcoming upgrade for the Air Force Reserve, National Guard, and active-duty USAF F-16s. Also, the latest USAF fighter acquisition, the yet to be built F-22, is currently engaged in a feasibility/cost study to equip the aircraft with an auto-recovery, AFTI based GCAS.

A DTED based GPWS or GCAS has significant advantages over other systems. Because the data is totally passive (no transmitting sensor) and "knows" the shape of the terrain, it is ideal for stealth missions. However, the DTED derived aircraft position must be correlated the aircraft's true position from the INS. The INS must be updated periodically from an outside reference to minimize drift errors, ideally from a Global Positioning System - GPS because it is passive. If GPS is unavailable, then the radar altimeter may be used (but is not passive). Using the DTED and a radar altimeter to provide update to the INS, the AFTI F-16 demonstrated few nuisance errors, accurate and repeatable terrain avoidance flyups, and "trust" by the pilots.

Of the 229 CFIT mishaps of all types (Class A, B, C, and HAPs) between 1980 and 1993, 72 percent of them would probably have been prevented if the aircraft were equipped with an auto-recovery GCAS. Likewise, 56 percent of them would probably have been prevented with a GPWS.

Cost Analysis

The prices for aircraft vary widely. Not only does the price vary between fighters and bombers, but the prices also vary significantly among aircraft within the same class (fighters, bombers, cargo/transport, or training aircraft). To simplify the cost analysis, a weighted average cost was computed weighted by the number of specific type aircraft within each of the four class of aircraft (Table IV-4). Based upon USAF data for the past 15 years, the CFIT mishap rate per 100,000 flight hours is computed for each aircraft class and an estimate for the number of likely CFITs is predicted for the future

(Tables IV-5, 6, & 7). The "average" cost and the estimated CFIT mishap rate is then used to estimate the likely future cost to the USAF as a result of CFIT mishaps (Table IV-8). Lastly, an estimate is made based on data from the F-15 and F-16 programs regarding the cost of developing, testing, manufacturing, and installing GPWS/GCAS systems on existing aircraft (Tables IV-9 & 10). Based upon a comparison between the CFIT mishap costs versus the cost to equip aircraft with GPWS and GCAS, the results show that it is cost effective to equip fighter/attack aircraft and bombers with GPWS or GCAS (Table IV-11). Equipping Cargo aircraft depends upon the price of the aircraft. The average cost for a cargo/transport aircraft is $50.6 Million, but these data are heavily weighted by older, cheaper aircraft such as KC-135 and C-141. Therefore, equipping older aircraft with and expensive GPWS or GCAS is not cost effective, but equipping newer aircraft such as the C-17 may be cost effective. The results are restated here:

		GPWS Prevent Cost ($M)			
		Time Horizon (years)			
Class	GPWS Cost ($M)	5	10	15	20
Ftr/Atck	178.3 *	297.7	595.4	909.6	1207.3
Bomber	38.8	140.2	210.3	350.5	490.7
Cargo	95.9	56.7	85.1	141.8	170.1
Trainer	91.2	2.2	4.4	6.6	8.8

		GCAS Prevent Cost ($M)			
		Time Horizon (years)			
Class	GCAS Cost ($M)	5	10	15	20
Ftr/Atck	284.2 *	382.7	765.5	1169.5	1552.2
Bomber	69.3	180.2	270.4	450.6	630.9
Cargo	N/A	72.9	109.4	182.3	218.7
Trainer	N/A	2.8	5.6	8.4	11.3

* includes USAF-wide, one-time $10M Mega-DTC cost (placed on fighters because they have already developed it)

A break-even analysis shows the number of years it takes for the four class of aircraft to recoup GPWS and GCAS investment costs from the number of likely CFIT mishaps prevented by having the aircraft equipped with GPWS/GCAS. The results are summarized in Table IV-12 and repeated here:

Class	GPWS - years	GCAS - years
Ftr/Atck	3.0	3.7
Bomber	1.7	2.4
Cargo	11.3	
Trainer	208.7	

Lastly, an equation is derived which mathematically describes the relationship between GPWS/GCAS costs, time span to break-even on GPWS/GCAS investments, CFIT mishap rate and number of CFIT mishaps per year, and the cost of an aircraft. It is a powerful equation because if two of the above variables are known or fixed (the number of CFIT mishaps per year is derived from historical data, and the time horizon could represent the service life of the aircraft in question), the remaining two variables are linked by a linear relationship. The equation is:

$$S = (\text{Time Horizon}) * M * P * C$$

where S ($ millions) = cost of either GPWS or GCAS in order to break-even at the time horizon (in years). Note: the cost includes flight test, development costs, etc.

M = number of likely CFIT mishaps in one year obtained from 1-year time horizon data in Table IV-7.

P = probability that either GPWS or GCAS will prevent a mishap. P= 0.56 for GPWS and 0.72 for GCAS

C ($ millions) = Cost of each aircraft

As discussed in Chapter IV, cost analysis summary, the cost and flying hour estimates are conservative. Aircraft costs are weighted with old, cheaper aircraft that will likely be phased out of the future USAF fleet and do not include avionic upgrades in their cost estimates. Additionally, the flight hour and CFIT rates used to make future estimates as far out as 15-20 years were derived using very recent (past 2 to 3 years) plummeting flight hour rates. Lastly, the cost estimates did not include any crew training cost lost as a result of CFIT fatalities (estimated as $1 million per pilot).

Resistance to Adopt GCAS

A significant number of pilots resist the adoption of GCAS onboard "their" aircraft even though the numbers show that it is both cost effective and a safety benefit. Psychological reasons include: (1) lowering (real or perceived) combat capability, (2) GCAS nuisance warnings, and (3) distrust of the system's ability to protect them. There is also USAF institutional resistance stemming from the complex, time-intensive acquisition process and because there is no single, focused push to equip USAF aircraft with a common (or similar) GCAS/GPWS.

Many of the pilots who are senior (General) officers today, flew in Vietnam and/or were commanders in the Gulf War. Like everyone else, they make decisions based on past experience. Unfortunately, in the past, they were frequently plagued by avionics or weapon system nuisance faults. These nuisance faults are something a pilot has very little tolerance for and can be very annoying. As a result, the decision makers in the USAF may be reluctant to equip aircraft with GCAS because they have heard (correctly) that GCAS is nuisance prone (even though the AFTI type system demonstrated low nuisance faults). Many pilots do not trust a computer to take control of their aircraft. It is counter to their training to let a computer decide their fate even though nearly all modern jet aircraft are digitally controlled. Lastly, and perhaps most importantly, pilots may feel that a GCAS equipped aircraft will limit the aircraft's (or their) ultimate combat capability. Pilots strive to take the machine and themselves to the "edge of the envelope" during training as well as combat in order to hone their skills for when they may need them. A GCAS system may limit them from taking the aircraft right to the edge because it must always work when needed. Remember that a GCAS/GPWS has the nearly impossible task of not activating when the pilot is aware of the imminent ground collision, but activating if the pilot is unaware of the danger. It needs to read his/her mind in order to not give nuisance warnings/recoveries. Since it cannot, it is usually more conservative (on the safe side) than desired by the pilots (note: this was not the case during the AFTI test program. On numerous occasions, the aircraft went closer to the "edge" than the pilots would have and as a result, more than a few pilots had their "pucker factor" increased by AFTI maneuvers which were inverted dives towards mountainous terrain).

Institutional resistance comes from a couple of sources. First are budget constraints. Every manager must make tradeoffs on whether to equip aircraft with systems intended for use primarily during peacetime (GPWS/GCAS systems) or spend money for systems which directly increase the effectiveness of aircraft/weapons during combat. Frequently GPWS/GCAS acquisitions are pushed to the lower end of the fiscal priority list even though they may increase the effectiveness of the USAF (the less aircraft lost due to CFITs means the more that can be employed during hostilities). Secondly, all USAF programs compete for the USAF budget. With the recent decline in the DoD budget, comes less money to spend on such improvements. Lastly, the GPWS/GCAS effort is unfocused across the USAF. Each aircraft program office is developing its own system, resulting in loss of economies of scale and a decrease in opportunities for realizing learning curve benefits.

RECOMMENDATIONS

Form a coordinated effort among the various aircraft System Program Offices (versus the current fragmented, independent efforts) to:

1.) *Equip fighter/attack and bomber aircraft which are currently equipped with standard Data Transfer Cartridges (DTCs) with the upgraded Mega-DTC, thereby providing a quite effective GPWS capability.* Doing so will provide:

- Digital Terrain Elevation Data (DTED)
- Terrain Referenced Navigation (TRN) needed to navigate using the DTED
- Manual TF capability cued by DTED/TRN
- Predictive GPWS (GCAS terrain hulling and flyup computation only. No auto flyup because flyup command/maneuver must be connected to flight control system for auto recovery)

2.) *Upgrade Digital fighter/attack and bomber aircraft with GCAS auto-recovery algorithms/ software during planned Operational Flight Program (OFP) upgrades.* OFP releases are very expensive (they typically cost anywhere from $30 million to $100 million depending upon the aircraft and extent of upgrade). Coinciding a GCAS upgrade (which requires a mod to the OFP) with a planned release will minimize cost and effort. GCAS capability is superior to GPWS (72% of CFITs are probably preventable if GCAS equipped, versus 56% with GPWS) and they are cost effective.

3.) *Consider upgrading analog fighters/attack and bomber aircraft (that are equipped with either standard or Mega-DTCs) with auto-recovery GCAS algorithms on the Digital Interface Cards (DICs) if cost effective and feasible.* GCAS capability is superior to GPWS (72% of CFITs are probably preventable if GCAS equipped, versus 56% with GPWS) and they are cost effective.

4.) *Investigate the feasibility of upgrading Mega-DTC aircraft with Global Positioning System (GPS) coupled to Terrain Navigation System.* Using GPS versus the radar altimeter will increase the correlation between the DTED map and INS-GPS derived reference position. It will also provide a stealthy GPWS/GCAS system. it also provides all weather GPWS/GCAS capability.

5.) *Cost effective analysis should be conducted on each individual cargo/transport type aircraft to ascertain whether GPWS upgrade is warranted.* The cost of cargo/transport aircraft varied widely (and was weighted by older, cheaper aircraft), thus GPWS/GCAS cost effectiveness is aircraft specific.

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13. Data regarding USAF implemetation of current GPWS and radar altimeter systems obtained through telephone interview with USAF Test Pilot, 410 Test Group, Edwards AFB, CA 93527, Dec 94 and Jan 95.

14. Data regarding GPS systems obtained through telephone interview with Edwards AFB Range Control Officer, 410th Test Group, Edwards AFB, CA 93527, Jan 95

15. Data regarding JPATS and GCAS/GPWS initiatives obtained through interview with Mr. Sam Jackson, Early Program Planning Office (Single-Face-To-the-Customer, SFTC Office), AFFTC/CA, Edwards AFB, CA. 92527.

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LIST OF ACRONYMS and ABBREVIATIONS

A	Attack
ACC	Air Combat Command
AF	Air Force
AFB	Air Force Base
AFTI	Advanced Fighter Technology Integration
AGL	Above Ground Level
AMC	Air Mobility Command
ANG	Air National Guard
AOA	Angle-of-Attack
B	Bomber, or $ Billions
C	Cargo
CFIT	Controlled Flight Into Terrain
Col	Colonel
DALT	Digital (determined) Altitude
deg	degrees
DIC	Digital Interface Card
DMA	Defense Mapping Agency
DoD	Department of Defense
DTC	Data Transfer Cartridge
DTED	Digital Terrain Elevation Data
F	Fighter
F/A	Fighter/Attack
FLIR	Forward looking Infrared
flt	flight
ft	feet (0.305 meters)
GCAS	Ground Collision Avoidance System
GLOC	G-Induced Loss of Consciousness
GPS	Global Positioning System
GPWS	Ground Proximity Warning System
HAP	High Accident Potential
helo	helicopter
HQ	headquarters
hr(s)	hour(s)
IMC	Instrument Meteorological Conditions
INS	Inertial Navigation System
IR	infrared
K	1000
knots	nautical miles per hour (6080 feet per hour)
LANTIRN	Low Altitude Navigation/Target Infrared for Night

lbs	pounds (0.454 kilograms)
LO	Low Observables (stealth)
LOC	Loss of Consciousness
Lt	Lieutenant
M	$ Millions
MCD	Minimum Clearance Distance
MDA	Minimum Distance Altitude (same as MCD, above)
mi	mile (1.609 kilometers)
min	minutes or minimum
nm	nautical mile (6080 feet or 1853 meters)
msl	mean sea-level
OFP	Operational Flight Program
ORD	Operational Requirements Document
OSD	Office of Secretary of Defense
PARS	Pilot Activated Recovery System
POM	Program Objective Memorandum
RALT	Radar Altitude
RAW	Radar Warning
RCS	Radar Cross Section
ROM	Read-Only Memory
SAM	Surface-to-Air Missile
SDO	Spatial Disorientation
sec	seconds
SPO	System Program Office
sq mi	square miles (2.59 sq kilometers)
T	Trainer
TF/TA	Terrain Following/Terrain Avoidance
TRN	Terrain Referenced Navigation
V_t	True-airspeed velocity
USAF	United States Air Force
VMF	Visual Meteorological Conditions

Greek Symbols

γ	flight path angle (gamma)
θ	pitch attitude (theta)

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