Head-Up Display Symbology for Ground Collision Avoidance

by

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Abstract

Four predictive ground collision avoidance displays (Break-X, Chevrons, Mountain, and Highway) were tested using a fixed-base T-38 simulator with a projection screen and simulated Head-Up Display (HUD). The Break-X was similar to the conventional military alert except that it remained on the screen until the aircraft was recovered to safety. The Chevron display consisted of two caret symbols (> <) which slid horizontally inward as danger increased, forming an X identical to the break-X. The Mountain display used a single icon which moved upward in the HUD as danger increased, mimicking the motion of the terrain outside. The Highway was a preview display, which consisted of a perspective elevated surface shown at the desired altitude.

Twelve subjects flew through a series of Predictive Ground Collision Avoidance System (PGCAS) situations in zero visibility using each display. For about 30 seconds after the alert, they attempted to maintain a set altitude above ground, clear of the terrain but below ground radar threats. Performance metrics were rolling tendency, altitude maintenance, pilot effort, and subjective preference.

The Break-X performed more poorly than the other displays in every category. It attracted attention but proved to be impractical for the terrain-following/terrain-avoidance task. Pilots were able to spend only 40% of the flight time between the desired altitudes when given the Break-X, and on average, they crashed every 5 runs. The Chevrons were more useful, although their horizontal motion did not correspond to the outside world. The Chevrons and Mountain averaged only one crash in 12 runs. The vertically moving Mountain had physical analogue, so pilots found it more natural to follow. This enabled them to spend approximately 80% of the time between the altitude limits, while the Chevrons allowed 70%. The better altitude performance from the Mountain came at the cost of higher effort levels, as shown by a significant difference in RMS longitudinal stick movement. However, a false illusion of wings-level produced slightly poorer roll performance from the Mountain. Pilots crashed the least using the Highway, averaging about one crash per 50 runs. It enabled them to fly approximately 90% of the time within the desired altitude layer. The Highway produced the highest objective and subjective ranking, and its predictive nature made it the best display for the task investigated.

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Mom and Dad, thank you for raising me right and for teaching me that hard work pays off. Two parents couldn't have been more supportive than you were of me. Wendy, Matt, Tom, and Megan, you are the best brothers and sisters a guy could ask for. Thanks for being proud of me.

Merilee, all I can say is I love you. You have been so supportive during our first two years of marriage, and I owe you everything for making the sacrifices you have. There is no one I would rather spend the rest of my life with. Thank you!

I thank God for the opportunity he has given me here. I am completely undeserving of His gifts: a loving family, good friends, a beautiful wife and, most importantly, eternal life.

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Geoffrey O. Billingsley

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List of Acronyms

AFTI .... Advanced Fighter Technology Integration
AGL .... Above Ground Level
AHP .... Analytical Hierarchy Process
ANOVA .... Analysis Of VAriance
ATC .... Air Traffic Control
CFIT .... Controlled Flight Into Terrain
CPU .... Central Processing Unit
DBTC .... DataBase Terrain Cueing
DTED .... Digital Terrain Elevation Data
DTS .... Digital Terrain System
EGPWS .... Enhanced Ground Proximity Warning System
FOV .... Field Of View
FPM .... Flight Path Marker
FY .... Fiscal Year
GCAS .... Ground Collision Avoidance System
GPWS .... Ground Proximity Warning System
GS .... GroundSpeed
GVS .... Gemini Visual Systems
HUD .... Head-Up Display
MC .... Minimum Clearance
MIL-STD .... Military Standard
NDB .... Network DataBase
NIMA .... National Imagery and Mapping Association
PGCAS .... Predictive Ground Collision Avoidance System
RAM .... Random Access Memory
RBS .... Range Bin Size
RMS .... Root Mean Square
SA .... Situational Awareness
SAM .... Surface-to-Air Missile
SCH .... Safety Clearance Height
TA .... Terrain Avoidance
TCH .... Target Clearance Height
TF .... Terrain Following
TFR .... Terrain Following Radar
USAF .... United States Air Force
WCH .... Warning Clearance Height

List of Abbreviations

deg .... degrees
ft................................. feet
g .... gravity
Hz .... Hertz, 1/sec
m .... meters
mrad .... milliradian
NM............................. Nautical Miles
sec .... seconds

List of Symbols

d_c .... Critical distance
F................................. Distribution parameter
t .... Distribution parameter
α................................. Probability of Type I error

1 Introduction

1.1 Problem Motivation

Controlled Flight Into Terrain (CFIT) is a major problem for today's low-flying military aircraft. In CFIT accidents, the aircraft is controllable and has sufficient energy to clear the terrain ahead, but the pilot's Situational Awareness (SA) is degraded to the point where a collision occurs. The degradation may involve limited visibility, cognitive tunneling, over-tasking, under-tasking, or a lack of altitude and/or attitude cues. CFIT is partially combated by Ground Collision Avoidance Systems (GCAS), known in the civilian sector as Ground Proximity Warning Systems (GPWS). GCAS warns the pilot just before the collision would occur, with the intention to allow a successful recovery.

A problem can occur, though, when visibility is limited and the pilot does not recover the aircraft to a reasonable altitude after receiving the alert. He may not pull hard enough or long enough, resulting in a CFIT accident. Alternatively, he may pull too long, unnecessarily exposing the airplane to ground radar and wasting valuable time and energy. In either of these two cases, the pilot does not have sufficient information about the terrain to plan a conservative, safe recovery. Part of the reason behind this may be the current standard visual alert provided on both the Head-Down Displays (HDD) and the Head-Up Display (HUD). When the GCAS issues an alert, the pilot hears an aural message such as, "Pull-Up! Pull-Up!" while an X symbol flashes on the HUD. The X then disappears after 2-5 seconds, leaving the pilot to his own devices to make the recovery.

The purpose of this thesis is to investigate several visual GCAS displays, which give the pilot additional guidance after the initial warning has been received. Specifically, it compares their ability to help the pilot recover to a safe altitude; clear of the terrain but low enough to preserve survivability in the presence of ground threats.

1.2 Thesis Summary

Chapter 2 provides background on CFIT, including the magnitude of the problem and causes behind CFIT accidents. It then details the advantages of digital terrain databases and discusses the theory behind and the implementation of Predictive GCAS (PGCAS). The shortfalls of current military PGCAS symbology are talked about at the end of the chapter.

In Chapter 3, several ideas are discussed as possible solutions to the symbology shortfalls. In particular, the section talks about dynamic PGCAS displays, which provide more information and better feedback to the pilot during a PGCAS-prompted recovery. These displays are alternatives to the break-X commonly used in most military aircraft. They include horizontally and vertically moving displays along with perspective symbology, which shows multiple terrain elevations to the pilot. The hypothesis is given at the end of Chapter 3.

Chapter 4 details the experiment used to test four candidate PGCAS displays, which fall into the categories mentioned in the previous chapter. The simulated ground collision avoidance algorithm needed to drive the displays is discussed first, followed by the symbologies themselves. The next section explains the hardware and software used to implement the simulation, and the last two sections review the simulation and the experimental design.

The results are presented in Chapter 5, which includes the subject demographics. The chapter quantifies the performance of the four displays during each phase of recovery. Subject comments are also included as a rich source of subjective data. The Analytical Hierarchy Process used to analyze the numerical questionnaire data is laid out in the last section.

The sixth and final chapter gives conclusions and recommendations drawn from the results of Chapter 5. Included are thoughts to be drawn from this research and further research that should be performed in the area of GCAS symbology.

2 Background

2.1 Controlled Flight Into Terrain

Controlled flight into terrain (CFIT) is a major cause of aviation accidents today. It occurs when the pilot unknowingly flies a controllable aircraft into the ground, generally due to a lack of situational awareness (SA). In these situations, the aircraft typically has sufficient energy and control authority to avoid the collision. Presenting terrain proximity information to the pilot in a concise, understandable way could prevent many of these accidents.

2.1.1 Problem Magnitude

CFIT accidents still occur in both civilian and military aviation, although the rates have been greatly reduced in recent years.[1] This is mainly due to federally mandated Ground Proximity Warning Systems (GPWS) and their military equivalent, Ground Collision Avoidance Systems (GCAS). Other improvements include better Air Traffic Control (ATC) radar coverage, Minimum Safe Altitude Warning systems, and better approach aids. Pilot education and simulator training have also contributed to the decrease. Still, an average of 31 turbojet and propeller aircraft were lost to CFIT each year from 1983-1992.[2] In the past 20 years, over half of the fatalities in airline crashes have been caused by CFIT.[3] The problem has by no means gone away, and today passenger aircraft crash at the rate of about one per year due to CFIT.

In military flying, some of the systems that have reduced civilian CFIT do not apply. Many missions are flown outside or underneath ATC radar coverage. Military pilots have motivation in many cases to stay *near* the terrain, not well above it. This flying is done in all weather conditions, at any time of day, and often these factors combine to cause CFIT accidents.

Between FY 1980 and FY 1997, CFIT was a causal factor in 176 of 945 total USAF Class A mishaps (almost 20%).[4] Class A mishaps are defined by complete loss of an aircraft, a fatality, or more than $1 million in damage.[5] CFIT accidents cost the Air Force an average of $181 million annually during this period. Many are fatal, and 170 of the 452 Air Force pilots killed during that time period died in CFIT crashes (almost 40%). The Air Force is not the only service plagued by CFIT. Between FY 1983 and FY 1997, the Navy and Marine Corps experienced 106 and 62 Class A CFIT accidents respectively.[6] This is a very real problem, and innovation is needed in the field to force these rates down.

2.1.2 CFIT Causes

In a CFIT collision, the aircraft impacts the terrain because the pilot is unaware of the aircraft's altitude or the increasing terrain altitude. This SA deficit sometimes arises due to a pilot workload that is too heavy or too light. The pilot may be fixated outside the aircraft, attempting to target another aircraft or an object on the ground. Examples are watching the bomb fall line and other targeting symbology just before weapons release, or checking visually to see whether those bombs hit the target.[7] Alternatively, the pilot might be occupied with something inside the aircraft such as a checklist or procedure. In both of these cases, the pilot's attention is devoted to something other than safe control of the aircraft. This is termed cognitive capture because the pilot no longer switches efficiently between the outside world and the aircraft or between different indicators in the aircraft.[8] This is especially applicable in military aviation, which includes maneuvering at low altitudes to avoid threat detection and operational tactics requiring high ground closure rates.[9] Tasks that commonly preoccupy the pilot are navigation, attack planning, threat evasion, and target acquisition at extremely low altitudes.[10] Of the 59 Class-A mishaps in the F-16 between 1980 and 1989, 53% occurred during low-level or maneuvering flight, and 60% were likely due to channelized attention.[7]

Another opportunity for CFIT is when the pilot lacks information about the aircraft's position. The aircraft slowly descends until it reaches the ground, or it remains at a constant altitude while the terrain below rises to meet it. This happens in environments lacking altitude cues.[9] Terrain devoid of features, like a snowy plain or sandy desert, gives little altitude information. Flight over the ocean sometimes leads to CFIT because the colors of water and sky can be quite similar, making the horizon almost invisible. Darkness, fog, smoke, and haze also eliminate many of the visual stimuli that would otherwise help the pilot remain aware of altitude.[9] Poor weather is a major cause, especially in military flying where aircraft are more likely to be near the ground when flying through clouds and fog.

2.2 Ground Collision Avoidance Systems

CFIT is partially mitigated through the use of military GCAS and the civilian equivalent termed GPWS. These systems were first fitted to jet transport aircraft in the mid-1970's and have improved greatly since then.[3] Originally, GCAS simply warned the pilot when the altitude above ground level (AGL), determined by the radar altimeter, went below a set threshold. Today, Predictive GCAS (PGCAS) and Enhanced GPWS (EGPWS) incorporate position, velocity, turn rate, and other factors to give a more accurate warning. Because PGCAS and EGPWS include predictive information, they are even more effective than their first-generation predecessors.

Based on current position and velocity, PGCAS projects a recovery maneuver that accounts for pilot and aircraft reaction time and a maximum performance pull-up. This is compared to a worst-case terrain profile based on the highest terrain the aircraft could feasibly encounter. Often, the terrain altitude ahead is extrapolated linearly using the radar altimeter. This works well in terrain that has zero or constant gradient, but in rugged hills and mountains the performance of these systems quickly degrades. Alternatively, the profile comes from a digital terrain database stored onboard the aircraft.

2.2.1 Digital Terrain

In the past, the only good sources of terrain information were terrain-following radar (TFR) and the radar altimeter. Both of these, however, have limitations. The radar altimeter gives only current information and cannot determine the terrain height ahead of the aircraft. Most are also roll-limited since the radar sensor must be pointing toward the ground for the instrument to function. TFR is relatively expensive, consumes space, and is limited by field-of-view. There are also time delays associated with slewing the radar and data processing.[9] Today, increased computational power in modern on-board flight computers and inexpensive flash memory have made possible an alternative: the use of digital terrain elevation data.[3] These data are generally taken from satellite surveys which are digitized at a set resolution to produce terrain maps. The maps include a set of latitude-longitude coordinates with a maximum terrain altitude at each location. Some even incorporate man-made obstacles like towers, antennae, bridges, and suspended cables.[11] The most readily available set of terrain data is the Digital Terrain Elevation Data (DTED) produced by the National Imagery and Mapping Association (NIMA). Generally, closer post spacing (better resolution) must be traded against coverage since the highest quality data are not available for the entire earth. Table 2.1 shows the DTED levels along with spacing and expected worldwide coverage.

Table 2.1: DTED Summary[12]

DTED Level	Nominal Post Spacing (m)	Expected Coverage (2001)
0	1000	100%
1	100	85-90%
2	30	80%

DTED is useful for terrain-referenced navigation, obstacle warnings, and passive ranging. The digital terrain data can also be used to improve PGCAS systems. If the flight computer has an accurate altitude profile of the terrain which the aircraft will soon fly over, look-ahead alerting can determine more accurately whether the aircraft is in danger of impacting the ground. These systems are sometimes termed Passive PGCAS (PPGCAS) because they do not rely on active sensors for terrain information, but the acronym is often shortened to PGCAS. Better terrain knowledge reduces the number of nuisance alerts, allowing pilots to trust more faithfully in their GCAS. Predictive Ground Collision Avoidance Systems can look over the horizon to provide earlier alerts, work well in turning flight, and are less expensive than active systems once the terrain database is established.[13]

2.2.2 PGCAS Algorithm

Generally, the PGCAS algorithm searches the database for terrain locations within a polygon ahead of the aircraft. The size and shape of the polygon may change based on the current aircraft state. For example, if the aircraft is in a right turn, the polygon can be expanded to the right since the terrain there is more likely to be encountered. Figure 2.1 shows typical shapes for the terrain search polygon in both straight and turning flight.[14,15] This terrain search pattern is similar to that used by British Aerospace in their Digital Terrain System (DTS).[16]

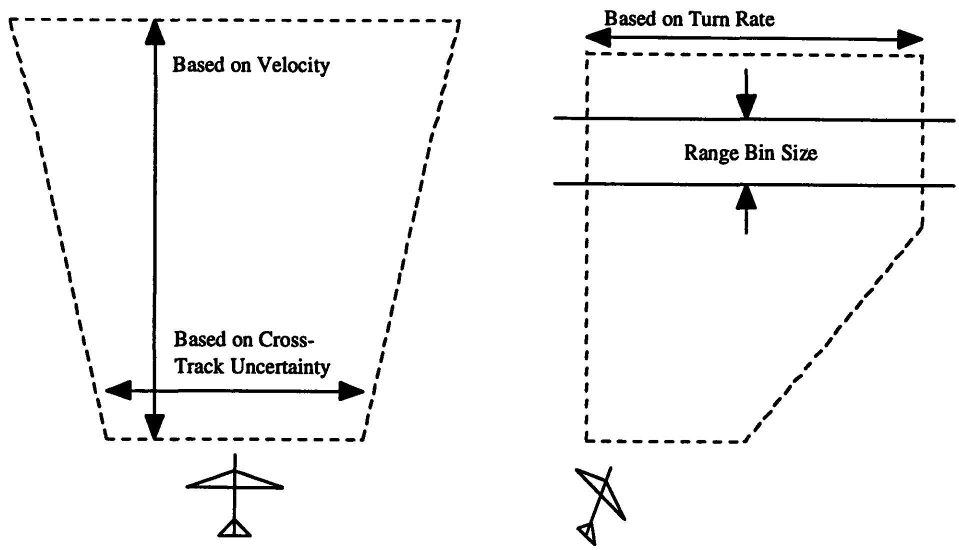


Figure 2.1: Terrain Search Polygons

The terrain posts that fall inside this polygon are analyzed using binning and hulling.[17] Binning involves a radial sweep across the polygon to find the highest post at each of a series of distances from the aircraft. The range bin size (RBS) is the distance increment at which these sweeps take place, and its choice involves trading accuracy for throughput. Making the range bins smaller means that less error will be made when they are hulled together. Binning compresses the polygon into a worst-case two-dimensional profile of highest terrain points. Hulling is the process in which the points are connected to estimate the terrain elevation between the posts. The hulls between the terrain posts are always convex to make the estimated terrain height conservative. Figure 2.2 shows the binning and hulling processes.

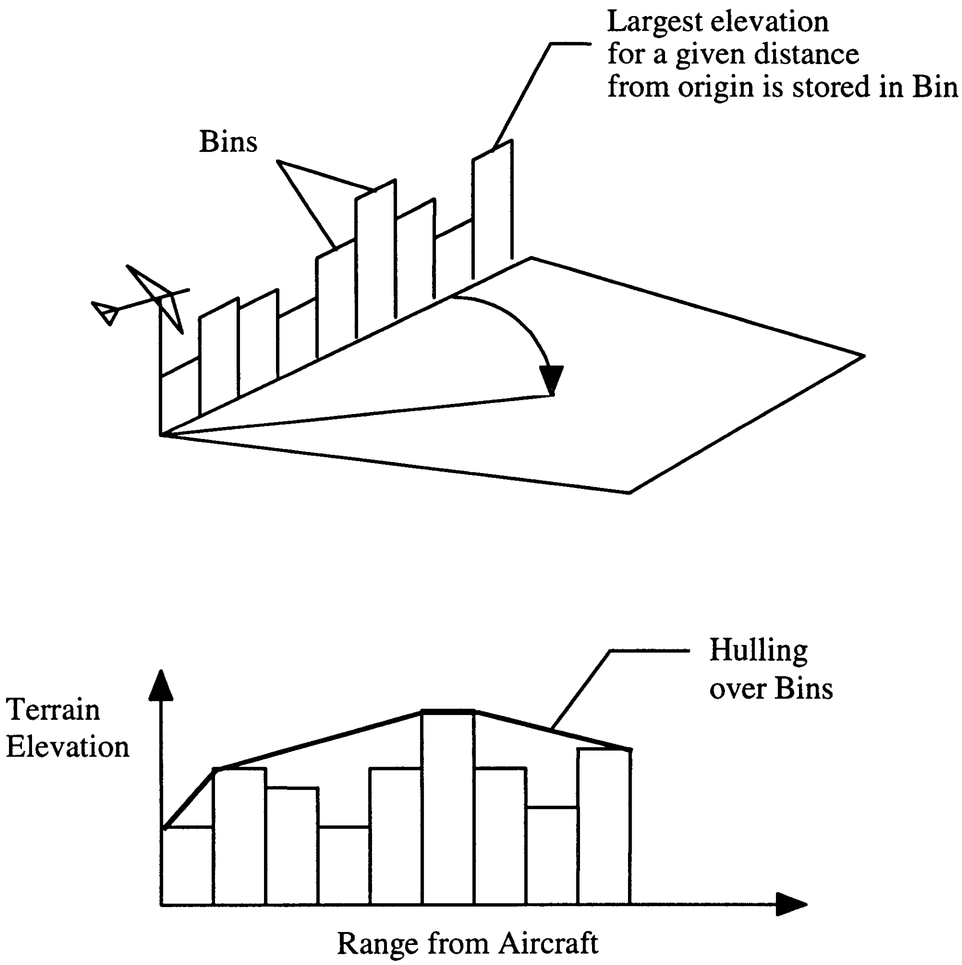


Figure 2.2: Binning and Hulling[14]

The PGCAS then projects a two-dimensional recovery, which accounts for pilot reaction time, roll to wings-level, g-onset, maximum-performance pull-up, and climb. The trajectory, calculated repeatedly, is an estimate of what the aircraft will do if the pilot receives a PGCAS alert at each point in time. It will continue toward the ground for an empirically determined pilot reaction time. The aircraft dynamics will determine the time needed to roll wings-level and then to reach the required load factor. The available load factor can be calculated from current aircraft speed, configuration, and weight to make the algorithm even more accurate. The pull-up is generally calculated using a constant radius based on the load factor, and the aircraft is expected to climb straight ahead after reaching some flight path angle. Figure 2.3 shows the projected recovery.

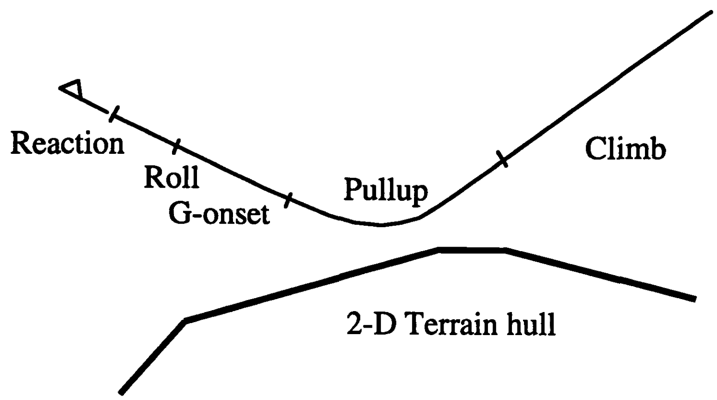


Figure 2.3: Projected Recovery

The warning is issued when the predicted trajectory comes too close to the terrain hull. The minimum distance between the terrain profile and the projected recovery is the parameter used by the alerting algorithm. An alert is issued when the distance no longer exceeds a safety clearance height set by the pilot. The safety clearance height is a function of the terrain type, area threats, aircraft performance, mission length, and other factors.

2.2.3 Current PGCAS Symbology

When a PGCAS call is received, both audio and visual cues inform the pilot. Usually, a synthesized voice in the pilot's headset exclaims, "Pull up! Pull up!" or "Altitude! Altitude!" Simultaneously, a unique symbol appears on the head-up display (HUD). The standard military PGCAS symbol, shown in Figure 2.4, is termed the "breakaway cue" or "break-X."[18]

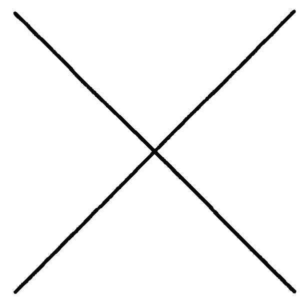


Figure 2.4: Break-X

It consists of two lines meeting at right angles to form an X, and it occults all other HUD symbology in most cases. The size of the symbol varies between aircraft, but the standard is about 100 mrad. The symbol flashes at a rate of 3-10 Hz, and it disappears completely after 2-5 seconds. It is usually located at the center of the pilot field-of-view (FOV) or in some cases at the flight path marker (FPM). The break-X is visible in most or all of the available HUD modes. This alert is used in the A-10, the F-16, and other fast-moving jets in the attack and fighter classes. When the pilot receives the break-X, training takes over. He or she knows instinctively that danger is present, and reacts by rolling to wings-level and pulling. Although pilots sometimes use a loaded roll (pulling while still banked), minimum altitude loss is achieved by first rolling to wings-level. The terrain features sometimes make a loaded roll more advantageous, especially when low terrain is seen to one side or the other. The pilot must then decide how hard to pull and how long to continue the recovery. The pilot uses a g-onset rate specified by the flight manual and pulls to maximum performance. Some aircraft provide natural cues such as buffeting when maximum performance is reached. They may also incorporate stick shakers or stall horns, which vary in frequency or magnitude to show the stall progression. In the A-10, which has few natural stall indications, maximum performance is found by pulling until the stall warning horn is "between the steady and chopped tones."[19] In any case, the pilot pulls up and then levels off or continues to climb based on the perceived terrain proximity and other factors.

2.3 Symbology Shortfalls

One problem with existing PGCAS is the fact that civilian and military pilots cannot completely rely on the system. When the alert occurs, pilots sometimes attempt to verify it before recovering by looking for other sources of altitude information (radar and barometric altimeter, visual scene). This period of time may be enough for the airplane to impact the ground, while an immediate recovery would have prevented the CFIT. This "delayed response syndrome" is partly caused by previously-experienced nuisance alerts, which desensitize pilots to the PGCAS. But it also may be contributed to by the on-off nature of the break-X. Because the symbol looks the same in any warning situation, a single bump in the terrain produces the same alert as a towering mountain peak ahead of the aircraft. If there were some way of putting the alert in context, such as a variable-intensity alert, the pilots would see not just the final warning but also the increasingly dangerous situation that led to the warning. Hopefully, they would be able to initiate the recovery immediately because they have already evaluated the situation.

The break-X originated while the radar altimeter was still the only source of PGCAS information, and since that time the display requirements have changed. And because more information is available for presentation, other symbols should be considered which would help the pilot in more situations. In a study of automatic and manual PGCAS recoveries, researchers at the Naval Test Center concluded that "Pilots rely heavily upon [visual PGCAS] cues to perform maneuvers such as a constant g pull-up to wings-level ... The more cues provided to the pilots about impending trouble ... the better."[20] Modern PGCAS algorithms discussed above already utilize terrain elevations at multiple distances from the aircraft. It is possible to show more of this information to the pilot without excessively cluttering the HUD. Benefits would include more confident low-level operation in deteriorating weather conditions, smoother PGCAS recoveries, and appropriate level-offs that preserve terrain masking.

2.3.1 Low-Level Operation

In many cases, military pilots perform low-level weapons delivery in marginal or poor weather conditions. They may be flying aircraft not equipped with a terrain-following (TF) system; in other cases TF is available but inappropriate. Consider the situation shown in Figure 2.5 where a gap exists between the terrain and the clouds that a pilot must penetrate enroute to the target. The problem is that he does not know what the weather or terrain looks like beyond that gap. He knows the gap is penetrable but feels unsafe flying through it, knowing that the ceiling may be down to the surface on the other side.

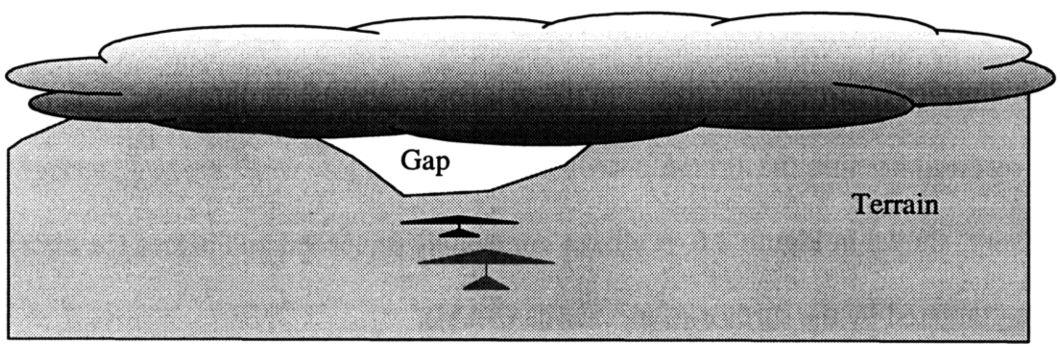


Figure 2.5: Penetration Gap

If the pilot could rely on the PGCAS for not just a last-minute warning but also real-time guidance through the terrain, he could confidently continue the mission. This would allow a weapons delivery in a situation where otherwise an abort might have occurred.

2.3.2 Smooth Recoveries

Leveling off after the recovery and wondering if another alert will occur gives an insecure feeling and adds to the already stressful situation. If the pilot wants to recover but remain fairly near the ground, he must weigh his safety against the chance that another alert will occur. If the break-X is to be used for recovering to an appropriate altitude and resuming the mission, the pilot must oscillate about the altitude where the break-X appears. This takes a large amount of pilot effort and is very dangerous because no indication is given until danger is already present. This makes the break-X impractical if not useless for staying above but somewhat close to the terrain.

2.3.3 Appropriate Recoveries

The typical break-X gives no visual indication when the aircraft is sufficiently recovered. The pilot would rather err to the conservative side, especially in instrument conditions. This results in large altitude gains in some cases, excessive in others. In cases where such a maneuver is really needed to avoid the terrain, it is appropriate. But in many situations, such aggressive action is unnecessary and even dangerous. Large altitude gains unnecessarily expose the aircraft, waste energy, use up valuable time, and disrupt missions. It is generally agreed that the hard pull-up is "not a manoevre to be encouraged in the vicinity of enemy air defenses."[13] Consider a PGCAS alert received because the aircraft descended slightly too low while crossing a ridge. The resulting recovery, shown in Figure 2.6, is almost completely unneeded and places the aircraft in danger of being targeted by the surface-to-air missile (SAM).

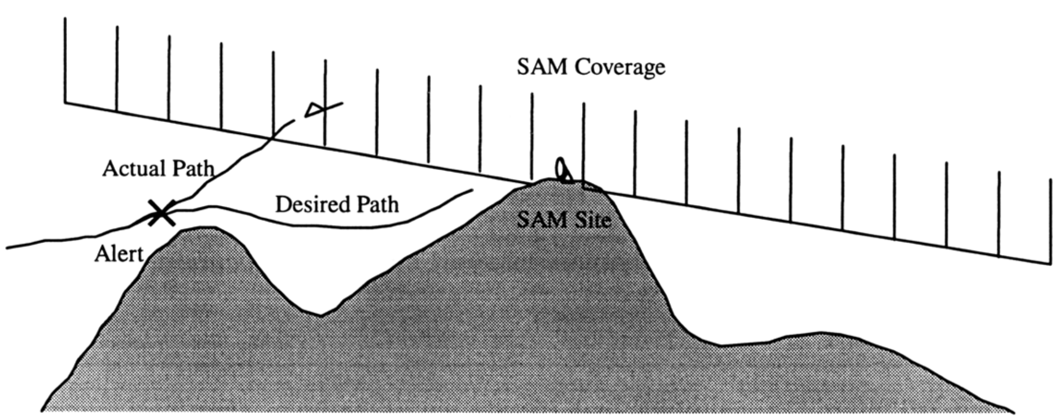


Figure 2.6: Ridge Clip Recovery

One can see that the aircraft recovers into the SAM coverage area where a shootdown might occur. The pilot really has no other option, though, because a collision with the terrain would be even more devastating. Generally, it is uncomfortable to descend in instrument conditions when one has just received a PGCAS call. In some situations, though, this may be necessary to preserve the stealth of the mission. In another situation, shown in Figure 2.7, an aggressive recovery is needed to clear the terrain.

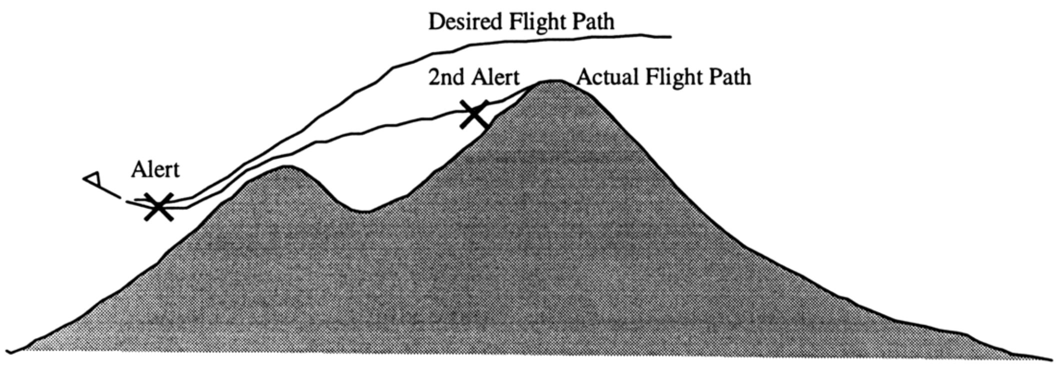


Figure 2.7: Insufficient Recovery

The pilot pulls hard to avoid the first ridge but leaves the throttle at less than full power because he cannot see the second ridge. Airspeed is lost during this pull-up, and when the second alert is received, the aircraft has too little energy to pull up and avoid the ground. If the pilot would have had an earlier indication that the second ridge was present, he could have used full power upon receiving the first alert and cleared both ridges. This type of CFIT accident would occur more often with a climb-limited aircraft like the A-10 because the pilot must make power adjustments early to conserve energy. Because the break-X is binary, it gives no information until danger is already present. It also gives information about the terrain at only one distance ahead of the aircraft, making it impossible to show the pilot *both* ridges in the previous scenario.

In the situations mentioned above, the break-X serves its originally intended purpose. It makes the pilot aware of the terrain and allows him sufficient time to react, roll, and pull. The problem is that no indication is given of the severity of the situation or whether the aircraft is no longer in danger of ground impact. A visual display should be considered to replace the break-X that provides more guidance to the pilot during and after the recovery. When the break-X was first implemented, the only information available from the PGCAS was that a recovery must be initiated. With predictive systems and digital terrain data, however, the system is much "smarter." It knows not just that high terrain exists, but also that terrain's distance and direction from the aircraft. It also knows what other ground features exist beyond the nearest terrain that may prove to be dangerous. A good PGCAS display would give the pilot some of this information, enabling more accurate, confident flying. Current research is investigating automatic PGCAS, which actually implements the recovery by taking control of the aircraft. This is not possible on many currently fielded aircraft, while changing PGCAS symbology is possible. Also, passive systems enable the pilot to maintain full control of the aircraft, which is desired in most circumstances if the pilot is adequately informed.[13]

3 Advanced PGCAS Displays

Visual symbologies should be investigated which show the pilot a safe recovery path or command him through one. The simplest of these recoveries would be a hard pull followed by a level-off at some safe altitude above the terrain. The altitude should be high enough that the PGCAS will not immediately trigger another alert, but it must be low enough that the aircraft remains within the desired constraints to avoid radar coverage. This altitude might change depending on the distance from the nearest SAM site. The display should not leave the pilot with an uncomfortable feeling when leveling off or descending, wondering whether he will impact the terrain. One improvement is to have an unobtrusive alert that remains on the HUD until the pilot physically acknowledges it by pushing a button or simply maneuvering to a safer altitude. Pilot feedback in the C-130 DTS project indicated that most pilots would like a consent/disregard button that would "indicate a positive pilot response for each [Passive PGCAS] warning." [12] Pilot comments in the development of KC-135 PGCAS indicated that "the GCAS warning should be present for as long as the warning conditions exist or until the pilot activates a GCAS system reset switch."[21] This would allow the pilot to decide when enough guidance has been received. This approach is more readily accepted by pilots of heavy aircraft because they are generally less task-loaded, and the crew of two has more time to positively acknowledge the alert. Even in fast-movers, though, the additional guidance and comfort provided by such a system might outweigh the nuisance of pilot-acknowledgement.

3.1 Possible Solutions

3.1.1 Horizontally Moving Displays

If the PGCAS alert is allowed to remain on the HUD until the pilot resets the system with a switch or recovers to safety, alternatives to the break-X would provide better guidance during the recovery. The first step in improving the alert might be to incorporate rate information to improve the binary nature of the break-X. Since the X-shape is commonly recognized as a PGCAS symbol, rate information could be added by splitting the X into two chevrons that move horizontally on the HUD (Figure 3.1).

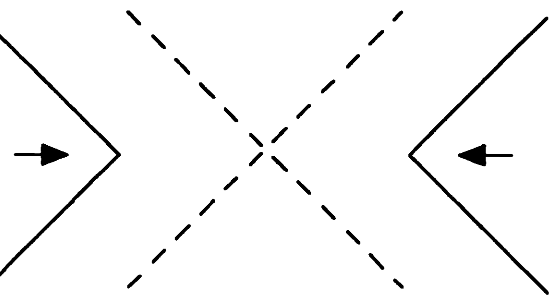


Figure 3.1: Chevrons

The pilot would see the two chevrons approaching one another until they form an X in the center of the HUD. This provides precursory warning information to the pilot, allowing him to examine the situation before the X appears, demanding immediate recovery. From the speed at which the chevrons come together, the pilot can also estimate his terrain-closure rate. A gain must be chosen so that the chevron movement is slow enough to be useful to the pilot but fast enough to provide plenty of advance warning. Pilots who flew an F/A-18 equipped with a chevron PGCAS display agreed that "... the chevrons provided several necessary cues ... that could be absorbed through their peripheral view. For instance, the rate of closure provided an easily perceptible cue on the sense of urgency of the situation."[20] Finally, the pilot sees the situation improve as he recovers. As he pulls, the chevrons slow their inward progress and begin to separate, providing positive feedback. The F/A-18 research noted that "Slowing of the closure rate or chevron separation provided useful feedback on if and how well the pilot was affecting the situation when he chose to intervene."[20] To remain somewhat near the terrain after the initial recovery while ensuring his safety, the pilot could fly so that the chevrons maintain some horizontal distance from center-HUD.

A chevron display is currently being used in flight testing of the Advanced Fighter Technology Integration (AFTI) F-16 Automatic GCAS.[22] The distance between the chevrons is based on the time until the Auto-GCAS recovers the aircraft, and the chevrons appear approximately five seconds before the initiation of the recovery. In the AFTI project, the purpose of the chevrons is primarily to provide precursory warning to the pilot before the active GCAS takes control of the aircraft. Chevron symbology, though, would also be very useful if used with traditional passive PGCAS.

3.1.2 Vertically Moving Displays

The chevron display seems useful, but an ambiguity exists. The horizontal movement of the chevrons does not correspond to the vertical motion that the pilot must command of the aircraft. Hence, the system lacks control-display compatibility.[23] This could confuse the pilot in times of duress because the horizontal motion does not correspond to the real world. The pilot might forget whether the chevrons' moving inward signals a better or worse situation. One possible solution is simply to rotate the chevrons so that they move vertically. The bottom chevron moving upward in the HUD would naturally correspond to the terrain outside moving upward in the pilot's FOV. The problem here is that the upper chevron might eliminate the correspondence because it would move downward as the terrain came upward. The natural solution is to eliminate the upper chevron (Figure 3.2). This would also reduce the redundancy of two objects moving at the same rate toward the same location.

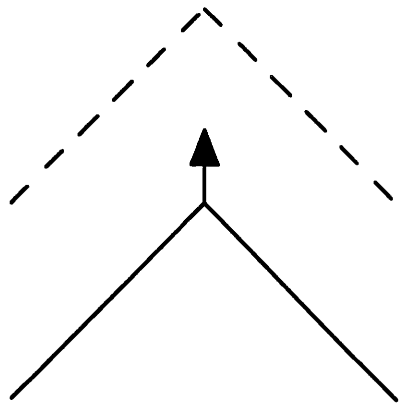


Figure 3.2: Vertical Chevron

If no upper chevron is used, the pilot no longer sees an X in the worst-case situation. Also, the chevron may be allowed to continue moving upward to the top of the HUD as the situation deteriorates beyond the point where the horizontal chevrons met. This change from the standard symbology would require additional training and a paradigm shift. The question also arises of what gain to use for the display and how to limit the symbol to the physical edges of the HUD. It can only move upward to the top of the HUD glass, so further vertical motion might be shown by changing the shape of the symbol once it is at the top.

The vertically moving chevron is similar in principle to the DataBase Terrain Cueing (DBTC) display used in the F-16 Digital Terrain System.[24] DBTC allows the pilot to follow the terrain at a set clearance altitude by maneuvering so that the FPM overlaps a box on the HUD. The box moves vertically to show the pilot how many "g" must be commanded of the aircraft to stay at the clearance altitude. The difference is that DBTC must be turned on and off; it is not designed to alert the pilot of an impending ground collision. The vertical chevron is also similar in concept to the kinematic horizon, which consists of "a single line nominally across the HUD indicating the horizon below which the flight path vector, as depicted by the flight path marker, must not be allowed to go."[13] The line can even show variations in vertical flightpath available to the left and right of the current groundtrack, as shown in Figure 3.3.[25,26]

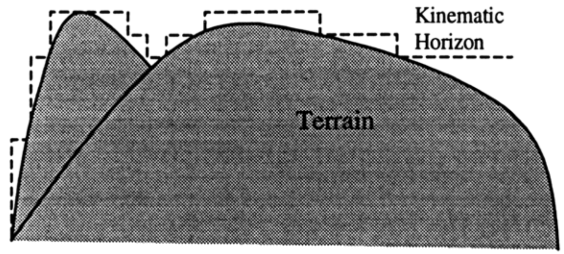


Figure 3.3: Kinematic Horizon

Both DBTC and the kinematic horizon are designed for terrain following (TF). "For military applications TF is extremely useful for long range penetration missions but it is far too inflexible for Close Air Support and many other roles requiring high maneuverability."[17] An advanced PGCAS display like the ones discussed here would allow that maneuverability and would be advantageous in both TF and non-TF equipped aircraft.

3.1.3 Conformality

If a symbol in the HUD (the chevron) represents something outside the aircraft (the terrain), the question arises whether to show the pilot the physical location of the terrain by making the display conformal. This means superimposing the chevron over the terrain feature that it represents. The question that must be answered if this type of display is to be used is which terrain to show the pilot. The display could show the terrain elevation at a set distance from the aircraft. The problem here is that the terrain between the aircraft and that point might be higher than the terrain displayed (Figure 3.4).

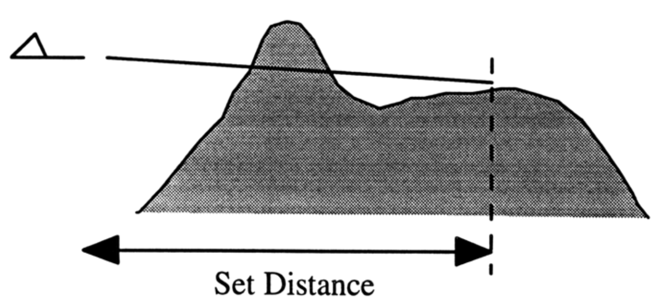


Figure 3.4: Terrain at Set Distance

Thus, the pilot is not given an accurate idea of the worst-case scenario. A second alternative is to show the maximum terrain elevation within the scope of the search polygon. A third option is to show the terrain that subtends the maximum elevation angle in the HUD. Finally, one could show the worst-case terrain as determined by the PGCAS algorithm. Another question is how to show terrain that lies outside the FOV of the HUD. If the most dangerous terrain lies just in front of the aircraft, it would subtend a large depression angle that physically cannot be shown on the HUD. Other issues include the symbol moving from one peak to another and the jitter that might occur. For all of these reasons, it seems impractical to make the vertical chevron display conformal even when the benefits are considered. A better alternative is to use a gain schedule like that used with the horizontal chevrons.

3.1.4 Multiple Terrain Elevations

The horizontally and vertically moving chevrons provide rate information, making them more useful than the break-X. Still, flight over a steep ascent or a sheer valley could make them move quickly with no warning. If this movement could be anticipated, the pilot could react more smoothly, hopefully using less effort and feeling more secure. To provide anticipatory cues, one solution is to show predictive terrain information. Showing the terrain at more than one distance would also help the pilot determine why the symbol was moving, whether from vertical aircraft motion or from changing terrain elevation. Another benefit of showing more than one terrain elevation is that many of the conformality issues are eliminated. The two-dimensional terrain profile no longer must be compressed to one symbol, so the question of which location to show no longer exists. The peak-to-peak jumps do not occur, and the pilot can determine from perspective and knowledge of the algorithm what the distance is to various terrain features. The display can thus benefit from the well-established advantages of conformality. Conformal symbology (representations of real-world features that conform to environmental contours) has been shown to enhance situational awareness. The pilot uses his own judgment during the recovery because he can see changes in the terrain height ahead of the aircraft. A conformal display that shows multiple terrain elevations is similar to the synthetic terrain display being investigated for helmet-mounted units. It is also similar to the highway-in-the-sky being evaluated for use in recovery and approach displays. "The highway symbols under initial evaluation are a series of ground-stabilised bars with upward pointing ends. The pilot flies along this highway without going below the bars."[25] The key difference is that the advanced ground collision avoidance display is used only when danger is present. The symbology appears when commanded by the algorithm and disappears when the aircraft is out of danger or the pilot acknowledges the call. Synthetic terrain research, though, can aid in the development of new ground collision avoidance displays to combine the benefits of both.

3.1.5 Perspective Displays

The perspective display is a natural way of showing multiple terrain elevations and could be created by extending the vertically moving display into two dimensions. The symbols representing more distant terrain are made smaller to make them appear farther away. One could use a series of horizontal lines or connect these lines to form a surface, a channel, or a tunnel (Figure 3.5).

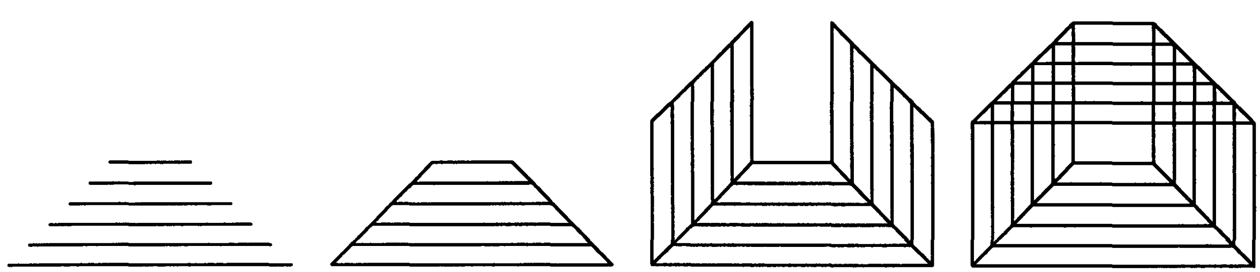


Figure 3.5: Perspective Display Options

One perspective display is the Spatial Situation Indicator presented by Williams and Mitchell for head-down approach guidance in commercial aircraft.[27] It utilized roll-stabilized vertical "whiskers" positioned at 15-second intervals out to 75 seconds along the aircraft flight path (Figure 3.6). The green lower portion extended from the predicted aircraft altitude to the terrain, showing predicted clearance at that point. The 2000-ft yellow portion was provided for comparative reference.

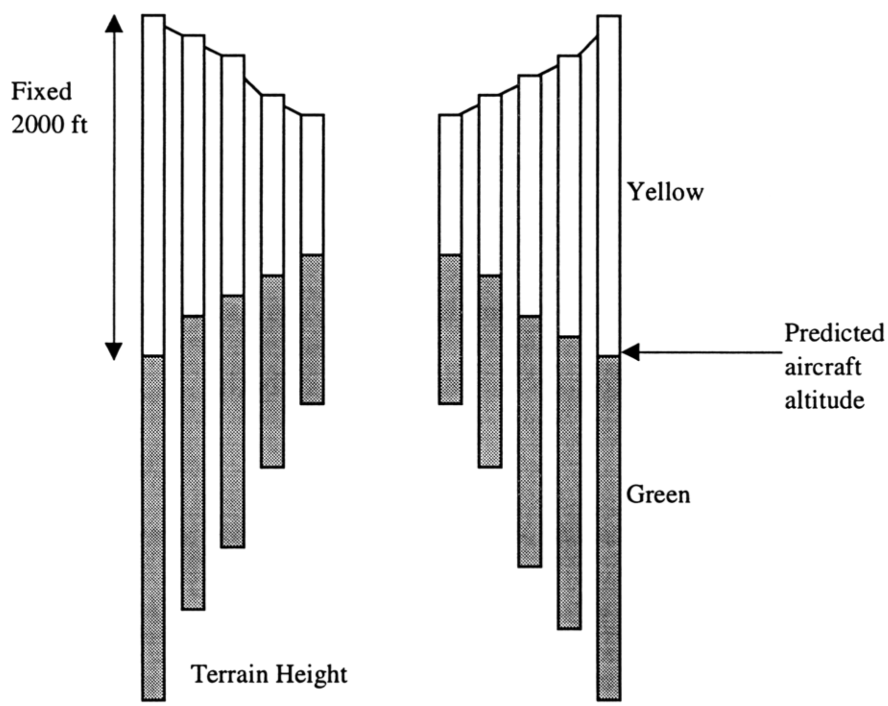


Figure 3.6: Spatial Situation Indicator

The perspective information given by this type of display is quite valuable. The human eye is already calibrated to judge real distances and angles. "Experiments with airline pilots showed that the perspective symbology reduced the pilot's workload and at the same time, improved the tracking of the demanded flight path."[28] The perspective display also helps integrate the multiple sources of information that the pilot would otherwise have to process: altitude, flight path, terrain altitude, terrain slope, etc.[28] In an examination of situational awareness, Wickens concludes that

"3D tunnel in the sky displays, in which the viewpoint of the display corresponds to the position of the pilot … are superior for flight path control."[29]

A key choice when a perspective display is utilized is whether to fix it to the earth or to the aircraft. When fixed to the earth, it appears to move past the aircraft, providing velocity cueing. It also provides instantaneous roll information because it moves with the horizon. These cues are desirable because the pilot can be more fully immersed and has fewer sources of information to assimilate. When the display is fixed to the aircraft, it can show the terrain along the flight path vector at any time. This is very helpful because the display "picks up" the most significant terrain as the aircraft changes heading. The ideal PGCAS display functions equally well whether the pilot decides to turn or recovers straight ahead. To provide guidance in any direction, an earth fixed display must show additional terrain off the flight path. This requires much more processing power and could clutter the HUD. To compromise, one can use an aircraft fixed display that is roll-stabilized. Thus, the pilot gains roll cueing and can see the terrain along his flight path vector without excessive clutter.

3.2 Hypothesis

This thesis hypothesized that the more informative displays discussed above would produce more accurate recoveries than the Break-X. In particular, the displays were hypothesized to be more accurate for altitude tracking after the initial recovery. The rate information provided by all but the Break-X would enable the pilot to fly more smoothly with less effort. It was also thought that the pilot would feel more secure and comfortable using the displays that provide more information about the terrain underneath the aircraft. This project proposed four candidate displays that fall into the categories already mentioned. The first was a break-X similar to the one currently in use. The second was a set of chevrons that moved horizontally inward to form the break-X, providing rate information. The third display was a mountain symbol that moved vertically upward, providing the same information as the chevrons but in the vertical direction. The fourth display was an elevated perspective highway attached to the aircraft, which showed upcoming terrain.

4 Experimental Setup

Four PGCAS displays were tested using a fixed-base T-38 simulator with a projection screen and simulated HUD. Twelve subjects flew through a series of PGCAS situations using each display, and data was recorded for a period of 30 seconds after each alert. They were instructed to fly at a set AGL altitude after receiving the alert, where they would avoid the terrain but also avoid ground radar threats. Examining how well the subjects recovered to maintain the set altitude allowed comparison of the displays' effectiveness.

4.1 Simulated PGCAS

In order to test the symbologies, a ground collision avoidance algorithm was needed to evaluate the terrain and provide input to the HUD. The algorithm used was a simplified version of the one implemented in many modern aircraft. The algorithm consisted of two pieces: a pull-up processor and a terrain processor. The pull-up processor created a two-dimensional "worst-case" trajectory, which accounted for a two-second pilot reaction time, a two-second roll to wings-level, a constant-radius pull-up, and a linear 60° climb. The maximum load factor available was a linear function of airspeed. Typical worst-case trajectories are depicted in Figure 4.1.

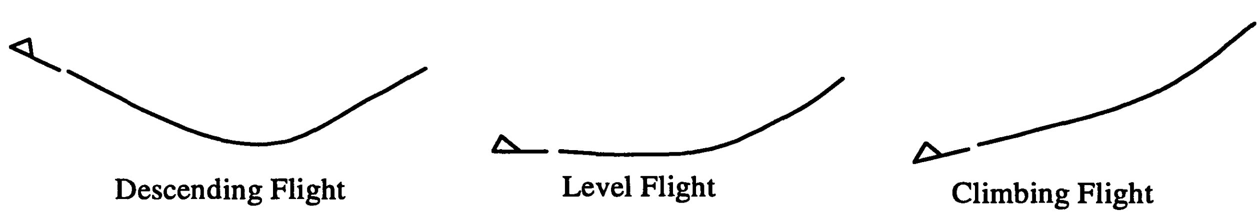


Figure 4.1: Projected Recoveries

The terrain processor compared the predicted aircraft altitude to the terrain elevation at a series of points projected along the aircraft's groundspeed vector. The points were spaced 500 ft apart and continued for a distance corresponding to 10 seconds at the current groundspeed (GS). The

500-foot spacing provided coverage of major terrain features without slowing down the frame rate noticeably. Figure 4.2 shows the line of terrain locations examined.

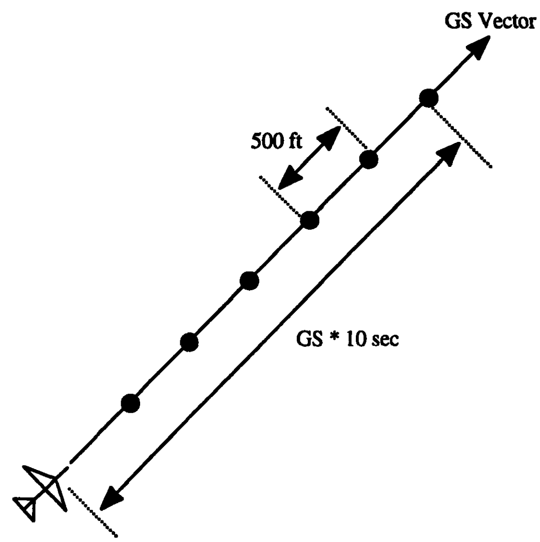


Figure 4.2: Terrain Evaluation Points

A real-world algorithm would evaluate the terrain enclosed by a polygon ahead of the aircraft to account for possible turns. For the simulation, though, a linear search pattern was sufficient to provide a predictive warning. The comparison between the projected recovery and the terrain produced a series of predicted terrain clearances, shown in Figure 4.3.

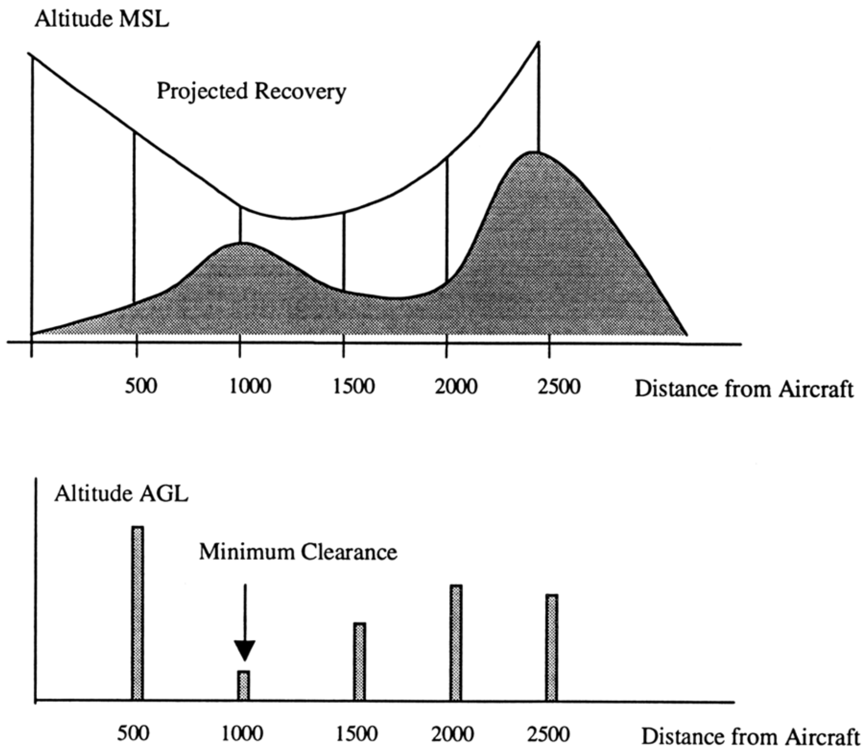


Figure 4.3: Terrain Processor Profile

To determine whether an alert would be issued, the minimum clearance (MC) was compared to the three clearance heights shown in Figure 4.4. These thresholds were the Warning Clearance Height (WCH), the Target Clearance Height (TCH), and the Safety Clearance Height (SCH).

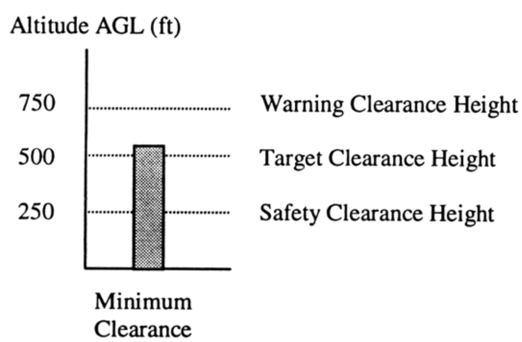


Figure 4.4: Clearance Altitudes

The WCH was the altitude at which the alert would first appear, and the pilot was told to stay below the WCH during the recovery to avoid ground radar. The TCH was the altitude at which the pilot was instructed to fly during the recovery. The SCH was the altitude which the pilot was instructed not to penetrate for safety reasons. These altitudes were considered realistic for low-level flight below ground radar coverage. The objective given the pilot was to recover the aircraft to safety and then fly at the TCH for about 30 seconds. This would simulate a situation where the pilot receives a PGCAS alert but wants to remain within an altitude constraint during the recovery. The alerts provided cues to aid the pilot in maintaining this altitude.

4.2 Candidate Displays

4.2.1 Head-Up Display

The HUD was the primary source of position and attitude information for the pilot. Figure 4.5 shows the HUD as it appeared in the experiment. The HUD FOV was 20° square, which is realistic for a modern fighter.

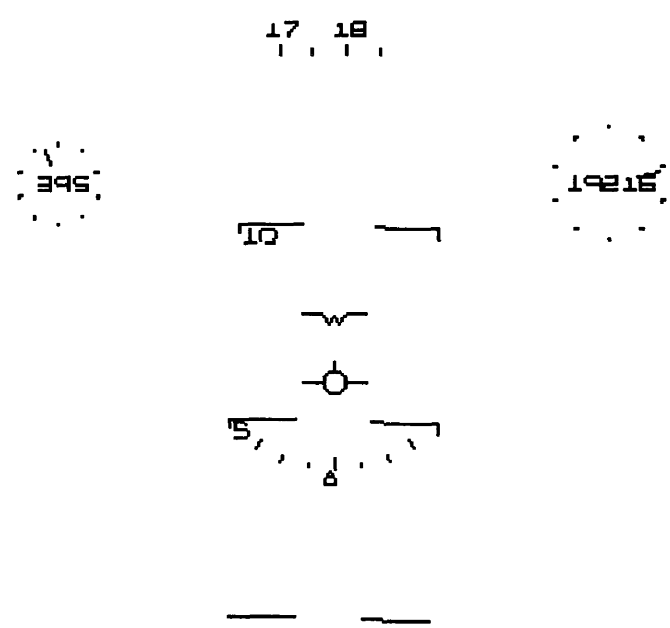


Figure 4.5: HUD Configuration

Airspeed in knots and barometric altitude in feet were displayed as circular dials containing digital readouts in the upper left and right corners respectively. Roll information came from the rotation of the flight path ladder and from the roll indicator scale and marker. The roll marker triangle was split into two sections that would separate in a sideslip. This provided yaw information although this rarely occurred. Heading in degrees was displayed on a moving tape scale across the top of the HUD. The aircraft reference symbol "W" was fixed to the nose of the aircraft to show pitch. Finally, the Flight Path Marker (FPM) showed flight path angle and was referenced to the flight path ladder.

The four PGCAS displays tested in this experiment presented similar information in differing formats. The Break-X was a discrete status display, which provided gross terrain proximity information. The Chevrons and Mountain displays were continuous depictions that provided position and rate information in a compensatory format. The Highway was a continuous display that provided position, rate, and acceleration information in preview format. Figure 4.6 shows how each display would appear when the minimum clearance was equal to 750 ft (WCH), 500 ft (TCH), 250 ft (SCH), and 0 ft.

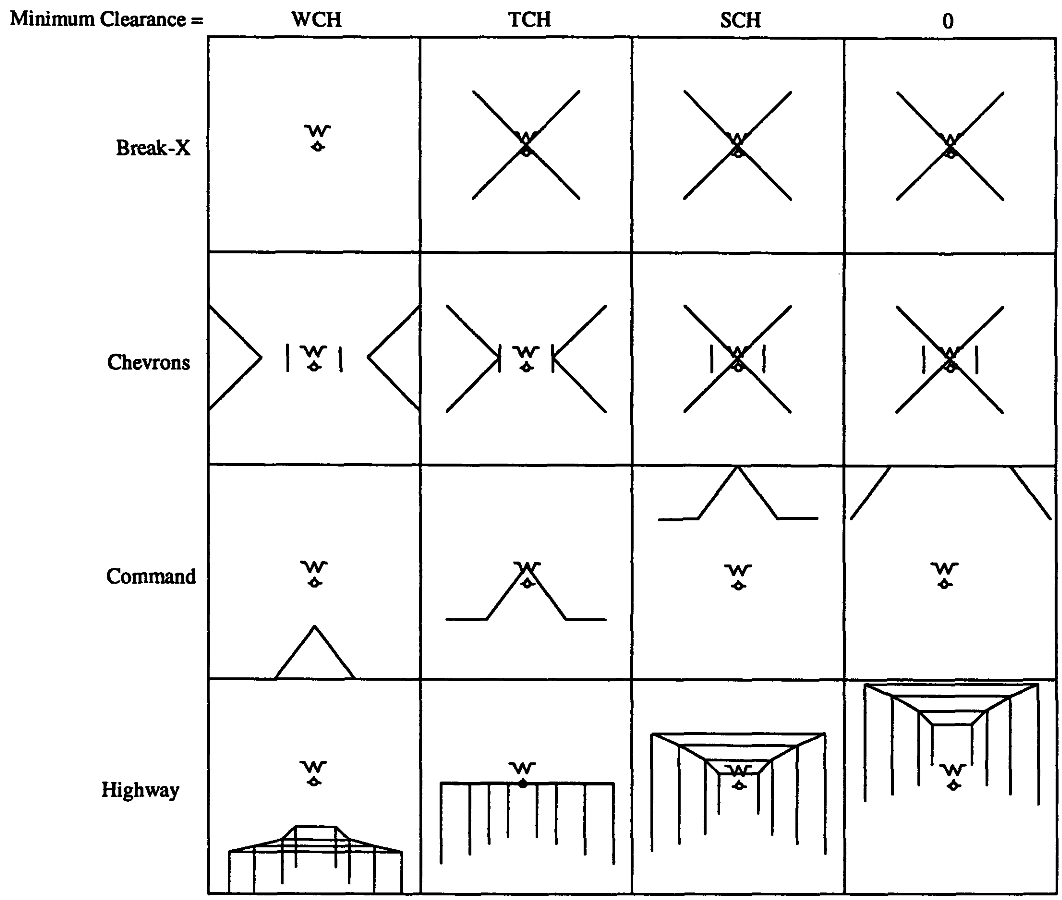


Figure 4.6: Display Summary

The displays were driven by the results of the simulated PGCAS algorithm. The scene-generation software performed the PGCAS calculations and produced the alerts in the HUD. All four were similar in size, although they occupied different locations on the HUD. Their sizes were based on the 100-mrad standard that is currently used in the Fairchild A-10.

4.2.2 Break-X

The Break-X (Figure 4.7) consisted of two 100 mrad lines crossing at 45° angles to produce a square X. It appeared at the center of the HUD when MC $\leq$ TCH and disappeared when MC > TCH.

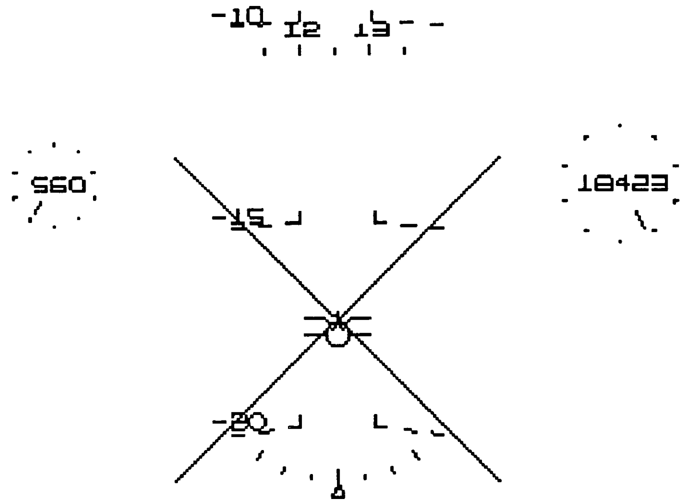


Figure 4.7: Break-X Display

The Break-X used in this experiment provided slightly more information than is given by the same alert in most operational aircraft. In the A-10, for instance, the "X" flashes for two seconds and disappears, giving no indication when the aircraft has been sufficiently recovered.[19] In this simulation, the "X" symbol was present until the aircraft climbed above the TCH to safety. This is the minimum standard that will likely be used when digital terrain technology is fully integrated. It was also necessary as a baseline to allow comparison between the four displays.

The Break-X was binary; it gave on-off information but no rate indication. Because it was the only binary display, it was expected to produce poorer quality recoveries than the other three. In truth, the break-X was not designed for a task such as the one tested here. It was engineered to get the pilot's attention, not to provide guidance during the recovery. When presented in combination with an audio warning, the break-X is a well-recognized symbol that alerts the pilot effectively. The reason for including it in this project was to show how poorly it might perform in a worst-case scenario. Worst-case means zero visibility flight near the terrain where a significant ground threat is present. In this case, making an overly conservative recovery to some altitude well above the terrain would prove impractical if not deadly. In visual conditions, the Break-X would gain back much of its usefulness. If the pilot can quickly survey the situation and recover appropriately upon receiving the alert, it is sufficient. But even when the terrain is visible, it might be useful to have some guidance on how hard to pull and when to level off. And because the HUD appears between the pilot and the terrain ahead, he can see the alert without focusing inside the cockpit. Thus, the other alerts mentioned here would be unlikely to *hinder* the pilot during a visual recovery.

4.2.3 Chevrons

The Chevrons (Figure 4.8) appeared at the left and right edges of the HUD when MC ≤ WCH. They moved inward as the terrain grew closer, and the tips just touched two 20-mrad vertical reference bars when MC = TCH. The chevrons formed an X in the center of the HUD when MC ≤ SCH.

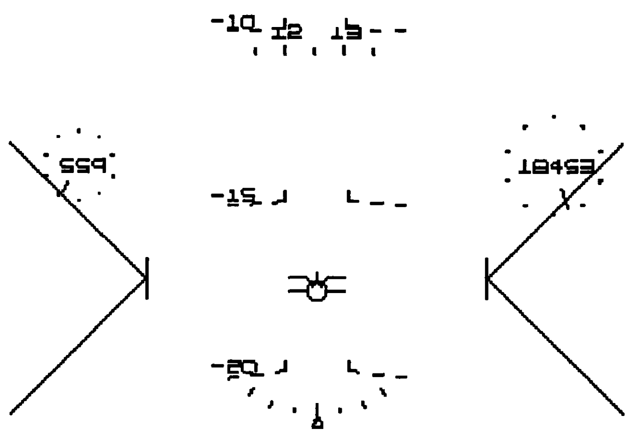


Figure 4.8: Chevrons Display

The chevron spacing was based on the distance between the minimum projected altitude and the terrain. Thus, the speed at which the chevrons moved together showed the terrain-closure rate. The question arose of choosing the gain that would determine chevron separation. In the end, only one gain would enable the display to meet the conditions specified in Figure 4.6. These conditions were chosen to put the displays on equal terms, allowing comparison between them. When the chevrons met in the center of the HUD, the pilot saw the familiar Break-X that has consistently been used. Because operational pilots are used to seeing the Break-X, this display would probably be adapted to fairly easily.

4.2.4 Mountain

The Mountain (Figure 4.9) appeared and moved upward from the bottom of the HUD when MC ≤ WCH. It was even with the fixed aircraft reference symbol ("W") when MC = TCH. It stopped moving vertically at the top of the HUD when MC ≤ SCH, and split at this point to become flat across the top. It touched the outside edges of the HUD when MC = 0, and soon after that the aircraft would impact the terrain.

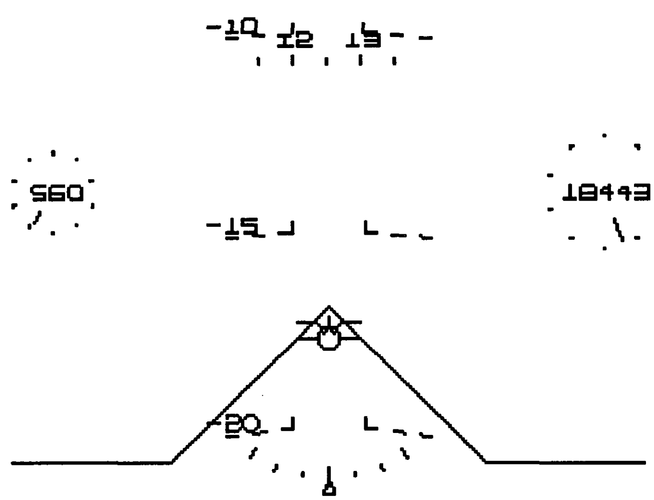


Figure 4.9: Mountain Display

This display provided essentially the same information as the chevrons, but it was oriented vertically. The mountain symbol moved up in the field-of-view as the aircraft descended, just as the terrain would do if the pilot could see it. The symbol could only move vertically to the top of the HUD glass, so further vertical motion was shown by the mountain spreading, as a real mountain appears to spread when rising in the field-of-view.

4.2.5 Highway

The Highway (Figure 4.10) was composed of horizontal and vertical lines drawn to show a perspective view of an elevated, roll-stabilized surface at the TCH. The legs of the highway extended to the terrain. The longitudinal spacing was chosen to show each terrain location being examined by the PGCAS algorithm, so the sets of legs were 500 ft apart. The width of the nearest bar just filled the 20° FOV. The bars became narrower as they showed more distant terrain. This is similar to the terrain contour specified in MIL-STD-81641, which consists of horizontal lines representing elevation angles to the highest terrain within each of five range increments.[18] The main difference was that the Highway had more than five range increments in order show all of the terrain being evaluated by the terrain processor.

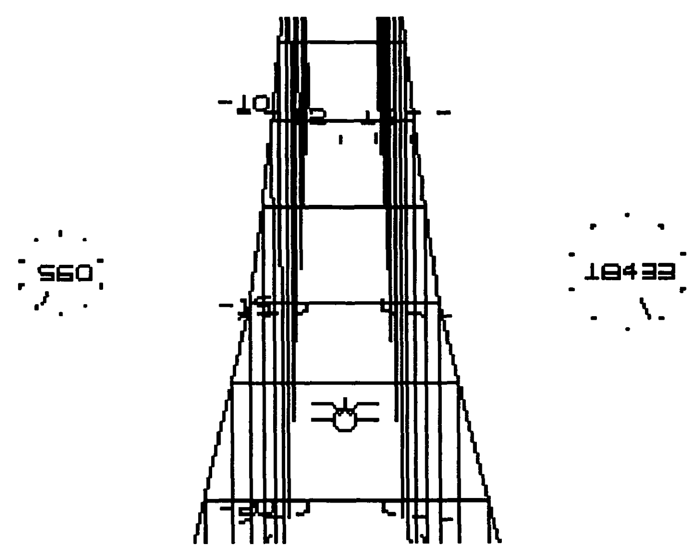


Figure 4.10: Highway Display

For the sake of the experiment, it seemed prudent to show the actual location of the TCH since this was the goal given the pilot. The location of the actual terrain was also important to show since the real danger existed at that level. The elevated highway symbology was chosen to show these two altitudes, and it had the additional benefit of resembling a physical surface. The Highway was the only conformal display of the four. If the pilot were able to see the terrain, it would have been at or just below the base of the legs. The surface showed the physical location of the Target Clearance Height, 500 ft above the terrain.

4.3 Hardware and Software

The simulation designed to test the four candidate displays used a fixed-base T-38 cockpit facing a 6'x8' projection screen. The synthetic HUD was projected on the screen, and simulated fog obscured the visual scene. The entire simulation setup resided on three processors - the first hosted the T-38 vehicle dynamics and timing routines, the second hosted the outside scene and HUD, and the third hosted the T-38 cockpit hardware input and output. Figure 4.11 shows a block diagram of the integrated simulation setup with specifications for each processor. All processors communicated through a common ethernet connection. The vehicle dynamics, scene generator, and cockpit I/O programs broadcasted and gathered information in a standardized format over a Network DataBase (NDB). The simulator program sent and received signals directly through a UNIX socket connection.

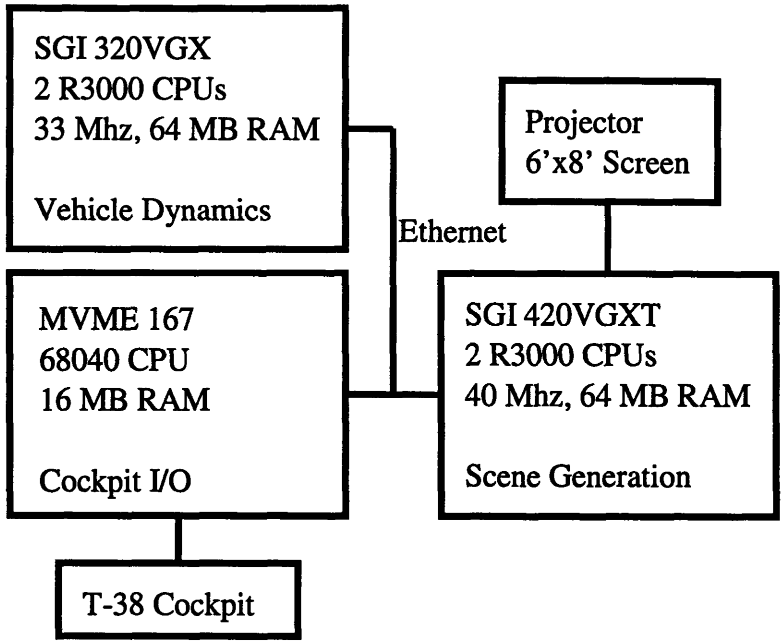


Figure 4.11: Simulation Hardware Block Diagram

4.3.1 T-38 Vehicle Dynamics

The Draper Laboratory T-38 vehicle dynamics simulator was chosen because of its robustness, flexibility, and commonality. Since it is the preliminary trainer in the fighter track, all USAF fighter pilots have flown the T-38. The vehicle dynamics program sent outputs to and received inputs from the scene and cockpit via the NDB. This program was the core of the integrated flight simulator. In addition to calculating the vehicle dynamics, it managed environmental factors and included data recording capabilities. The simulation ran at about 120 Hz (time-step of 0.0085 sec).

4.3.2 T-38 Cockpit

The T-38 cockpit was used to make the simulated flight experience more realistic. It provided a pilot interface consistent with operating an actual fighter. The cockpit included a number of analogue and discrete channels for controls. The controls utilized for this experiment were the stick and rudder pedals. The trim and flap switches provided inputs to the simulation, but remained fixed at neutral and flaps up respectively. The two throttles were fixed at full military power. The cockpit appears in Figure 4.12.

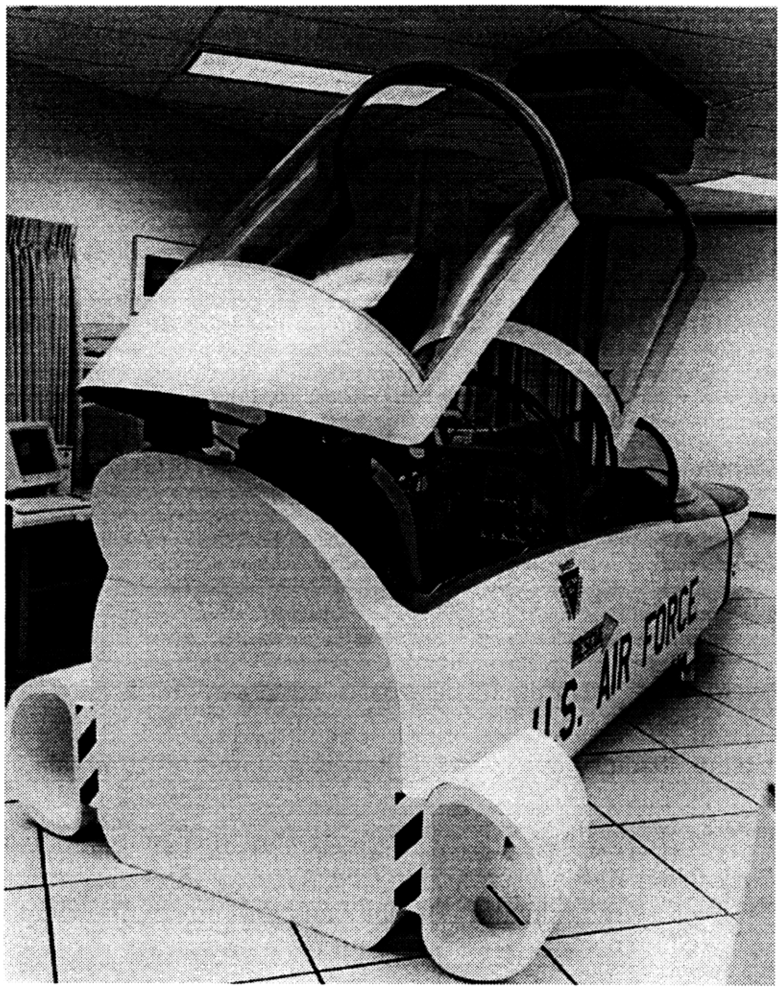


Figure 4.12: T-38 Cockpit

4.3.3 Data Recording

Variables recorded included: time, aircraft position and rates, Euler angles, rates, and accelerations, stick position, load factor, alert symbology position on the HUD, and terrain altitude. The data were recorded at a rate of 12 Hz. The simulation framework included the capability to log data, which were converted and analyzed.

4.4 Simulation

4.4.1 Visual Scene

The HUD was generated using the Gemini Visual System (GVS) SIMation Series Software graphics package. The GVS software included functions for building and manipulating scene objects and creating viewing "cameras" and attaching them to objects, as well as pre-built objects and textures to be used in a scene. Nothing in the scene was visible to the pilot except the HUD and PGCAS symbology, drawn as black lines against a cloud-gray background. The frame rate produced by the GVS software was generally near 30 Hz. The GVS software was also used to perform the simulated PGCAS calculations because of its immediate access to the terrain database.

4.4.2 Flight Director

The desire was to test the four displays at a variety of flight path and bank angles. To achieve a specified alert attitude, the pilots followed a series of commands given by a flight director on the HUD. The flight director symbology appears in Figure 4.13. The pilots pitched to superimpose the FPM over a flight director dot and banked to match the wings of the FPM with a line across the dot.

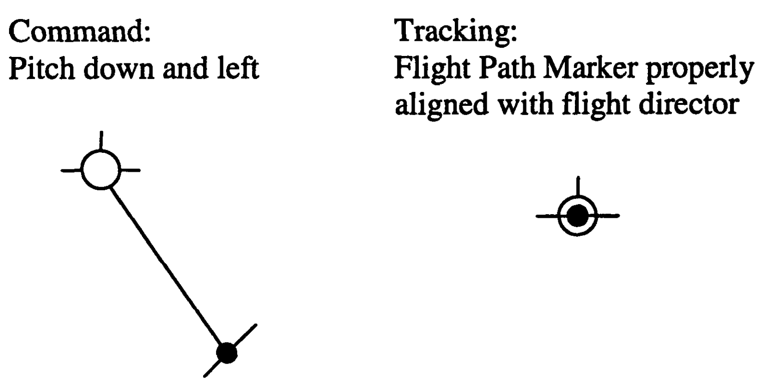


Figure 4.13: Flight Director Symbology

The flight director would remain at a given flight path and bank angle until the pilot was able to match the command within ±2° of flight path and ±5° of bank for 4 seconds. It would then smoothly transition to the next position on the HUD. The subject followed the flight director through one, two, or three commands before reaching the final alert attitude.

4.4.3 Terrain

The terrain database was created using satellite imagery taken in Yellowstone Park, Wyoming. The image shown in Figure 4.14 was texture-mapped over multiple polygons created from digital terrain data, creating three dimensional mountains, valleys, and plains. The terrain block represented in the photograph is 7.5 NM square, and the picture is oriented with North up.

Figure 4.14: Yellowstone Park Terrain

This terrain block was mirrored multiple times to create a database large enough so the pilots could not fly off the edge of the terrain. Since the terrain was invisible in the simulation, only terrain elevation information was taken from this database. The PGCAS algorithm could query the database for terrain elevation at any X-Y location. Linear interpolation enabled the algorithm to determine the terrain elevation between two data posts.

It was desirable for the pilots to receive each alert at the same x-y location, altitude, and heading. This would make the terrain encountered nearly identical and would aid in comparison of the resulting trajectories. To mechanize this, the simulated aircraft was programmed to instantly jump to a pre-specified location and heading when the pilot met the final command. This was not apparent to the pilot because the altitude and heading jumps were not shown on the HUD and the terrain was invisible. This was important to ensure the pilot was not aware when the alert would be triggered. The aircraft always jumped to an altitude such that the PGCAS algorithm would trigger an alert approximately one second after the jump. The aircraft jumped to one of two different locations where it would encounter either smooth or rugged terrain. The purpose for using the two terrain types was to determine whether some displays performed better than others did over a certain type of terrain. Figure 4.15 shows representative terrain profiles for the smooth and rugged terrain. All of the profiles encountered had the same basic shape as these two; any variations were caused by differing bank angles between successive runs.

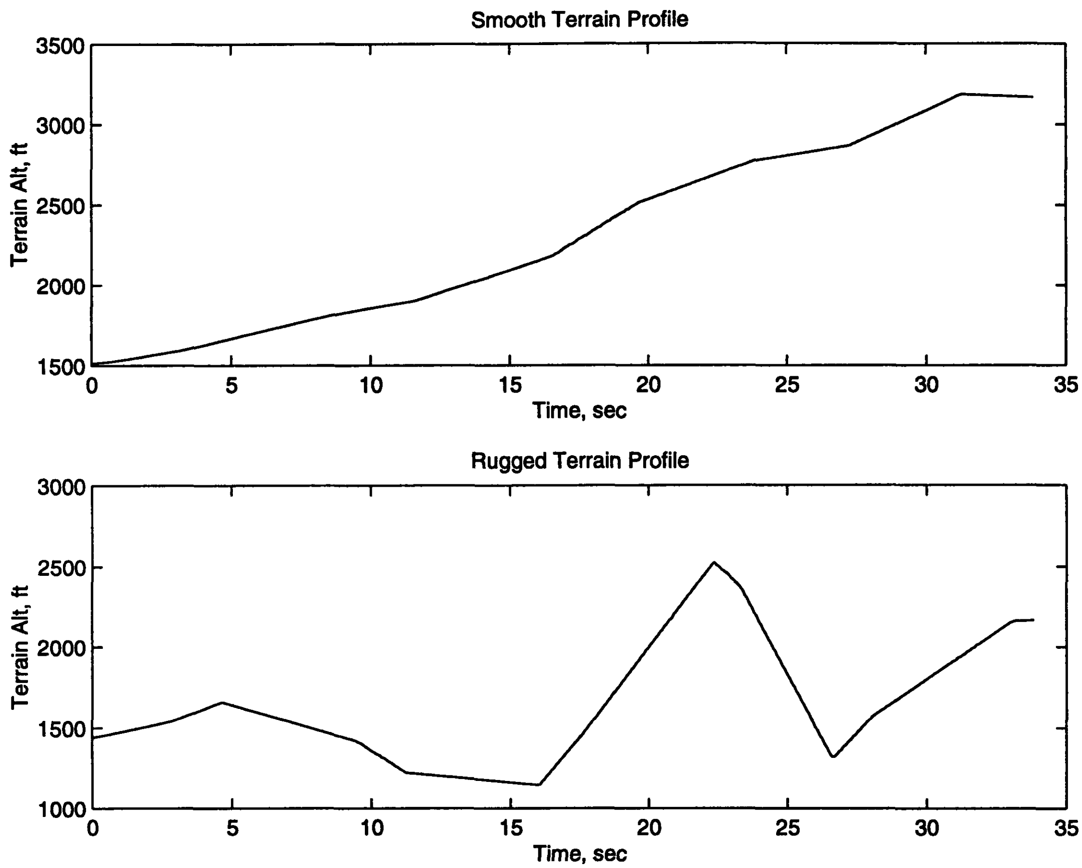


Figure 4.15: Terrain Encountered

For the purposes of the simulation, the aircraft was allowed to fly lower than the terrain surface without pausing the simulation. This was artificial since a crash would occur in the real world, but it was necessary to provide continuous altitude information. To inform the pilot when the aircraft was in the crash condition (AGL altitude less than zero), a black shape resembling a bent-up pitot tube was shown on the HUD. This happened very seldom, and any pilots who saw the pitot tube were already in the midst of a recovery. Thus, the crash indication had very little effect on the pilot actions.

4.5 Experimental Design

4.5.1 Protocol

Each subject was told the purpose of the experiment and given some background on PGCAS. He then read the directions (Appendix A) and signed the consent form (Appendix B). The subject became familiar with the controls and was given time to practice following the flight director. Next, he was allowed to practice with the first display and ask questions about it. Once comfortable using the display, the subject flew six runs. Each run consisted of following a series of HUD visual commands to place the aircraft in a predetermined alert attitude. A PGCAS alert was triggered, the pilot recovered, and data were recorded for about 30 seconds. The six runs were followed by an oral interview before moving on to the next display. The experimenter recorded the pilot's responses to the survey questions, included in Appendix C. The 6 runs and interview were repeated for each of the other three displays. Then the subject exited the cockpit and filled out the remainder of the questionnaire. Each subject flew 6 runs on each of 4 displays for a total of 24 runs. The set of 6 runs, which appears in Table 4.1, was identical between displays and between subjects. The table lists the flight path and roll angles in degrees along with the type of terrain encountered during that run.

Table 4.1: Test Matrix

Run	Terrain	(Flightpath, Roll Angle)			
1	Smooth	(15, -15)	(-5, -30)	ALERT	
2	Rugged	(-5, 15)	(5, 30)	(-15, 0)	ALERT
3	Smooth	(-25, 30)	ALERT		
4	Rugged	(15, -15)	(-5, -30)	ALERT	
5	Smooth	(-5, 15)	(5, 30)	(-15, 0)	ALERT
6	Rugged	(-25, 30)	ALERT		

4.5.2 Counterbalancing

The experiment was counterbalanced to account for learning, fatigue, and other order effects; Table 4.2 shows the resulting order

Table 4.2: Balanced Design

	Subject											
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
1st Display	X	X	H	H	H	H	X	X	C	M	C	M
2nd Display	C	M	C	M	X	X	H	H	M	C	M	C
3rd Display	M	C	M	C	C	M	C	M	X	X	H	H
4th Display	H	H	X	X	M	C	M	C	H	H	X	X

X = Break-X **C = Chevrons** **M = Mountain** **H = Highway**

To help reduce the number of required subjects, the displays were balanced in a blocked fashion. The Break-X was iconic and discrete, standing by itself. The Chevrons and Mountain presented similar continuous information in horizontal and vertical formats, so they were blocked together. The Highway presented predictive information and also stood by itself.

5 Results

5.1 Subject Demographics

The subject pool consisted of military and civilian graduate students and employees of Draper Laboratory. The subjects were required to have a Private Pilot rating or equivalent, which would enable them to understand the simulation. This ensured that the subjects could correlate their experience with real-world flying and that they were familiar with aircraft controls. The twelve subjects, all male, had an average of 820 total flight hours. Six had experience in instrument conditions, nine had simulated or real experience with Head-Up Displays, and ten had military flight experience. The subjects ranged from 22 to 54 years old with a mean age of 31.

5.2 Subject Performance

To compare the four displays analytically, an Analysis of Variance (ANOVA) was applied to the data to obtain the F-statistic with 95% confidence (α = 0.05). This would determine whether performance differences were due to chance or to the differing alerts. If there was a significant difference between the displays, the Link-Wallace test was applied to determine the critical distance (d_c) between means[30]. The distance d_c is the minimum difference between means that must exist in order to be statistically significant. The critical distance was compared to the mean difference between each pair of displays to determine which ones were more effective than others. The error bars shown on the following plots represent d_c, so a significant difference exists if the bar height for one display exceeds the error bar for another.

5.2.1 Roll to Wings-level

The first part of the recovery involved the roll to wings-level. One of the items being investigated was whether any of the displays performed significantly better in helping the pilot roll initially and to maintain the wings-level attitude throughout the recovery. Leveling the aircraft quickly is important because the minimum altitude is lost during the recovery if the roll occurs before the pull-up. With some of the displays, the pilots tended to recover the aircraft while maintaining a bank angle, which could prove dangerous in a real situation. Figure 5.1 shows time histories of roll angle, which represents roll error since the desired angle was zero. The alert was issued at time zero, and the grouping during the first few seconds resulted from the three initial roll angles: 30°, -30°, and 0°.

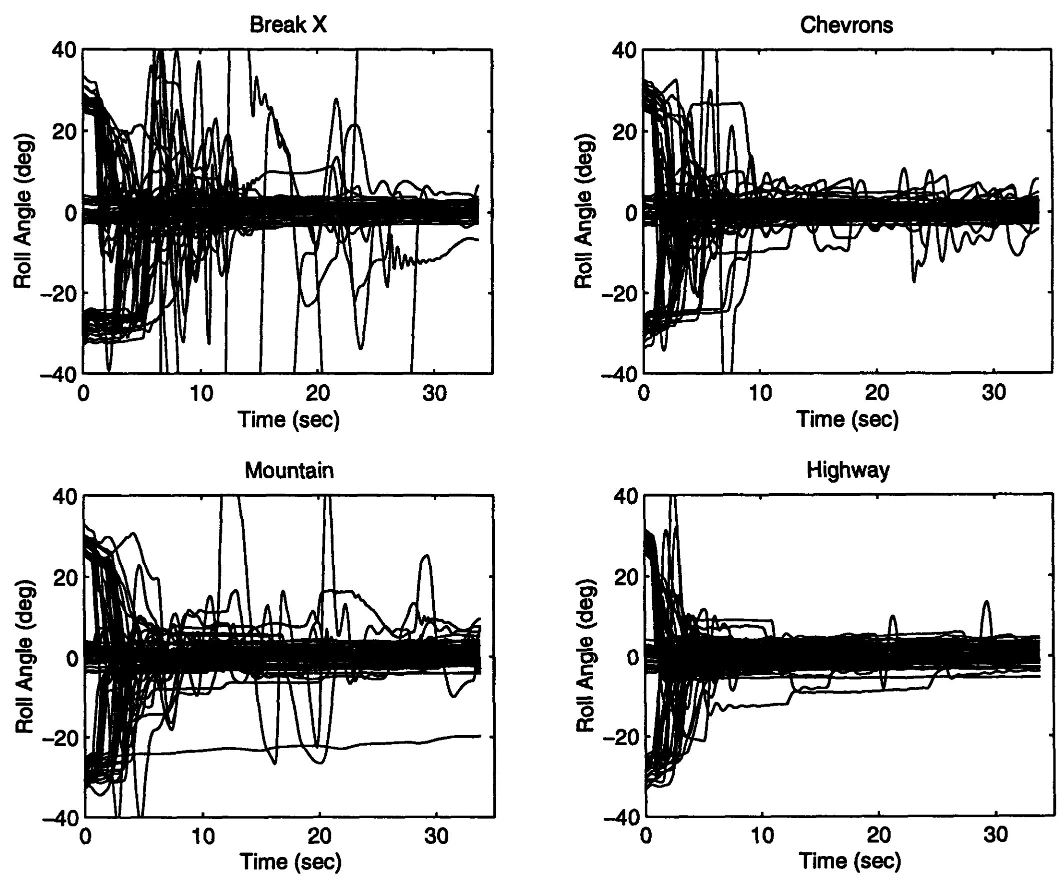


Figure 5.1: Roll Angle Histories (72 cases)

The figure shows that the Break-X produced numerous recoveries at significant roll angles. The Highway produced the tightest grouping, followed by the Chevrons. Note how quickly the

Highway grouping narrows to near zero. This reinforces pilot comments that the Highway naturally cued the pilot to roll to wings-level.

Because roll in either direction is equally undesirable, the metric used for roll performance was RMS roll angle, averaged between runs and between subjects. Figure 5.2 shows the RMS roll angle for the four displays.

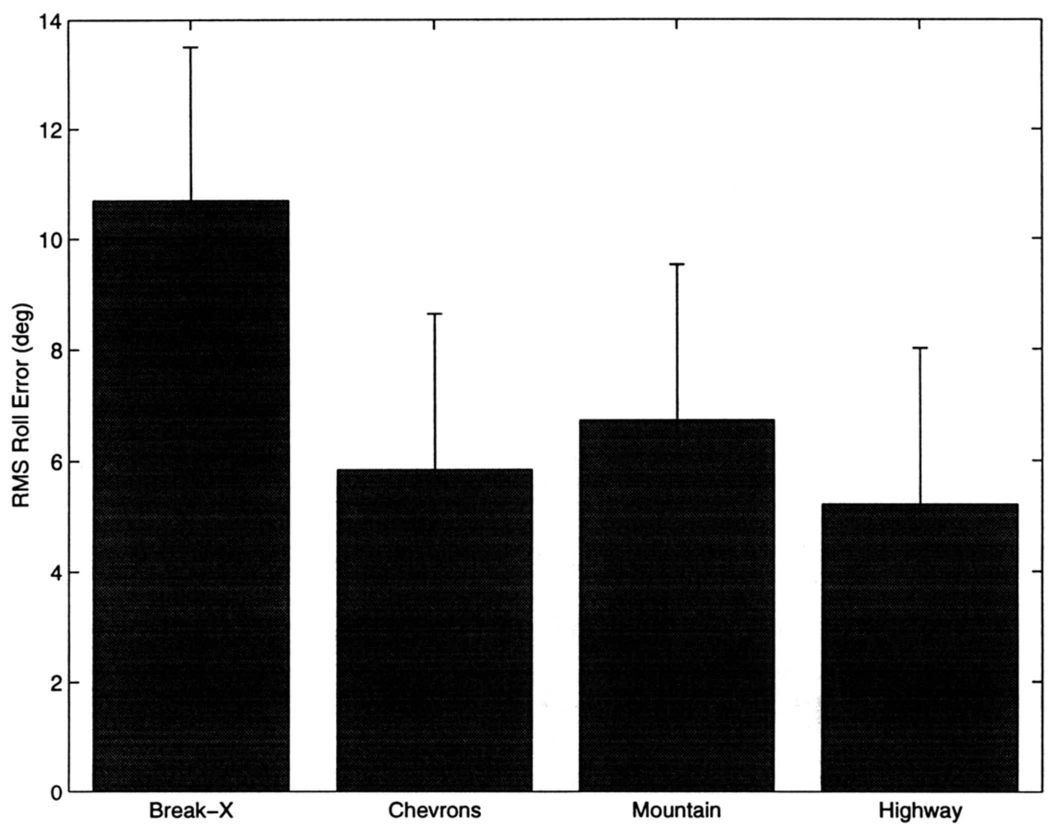


Figure 5.2: RMS Roll Angle (n = 72)

One can see that the Break-X produced significantly more roll error than the other three displays. This is somewhat surprising because with the binary alert, the pilot did not have a tracking task like he did with the other three displays. One might expect that the pilot could pay more attention to bank angle without the tracking task and therefore accumulate less RMS roll error. One reason for the poorer Break-X performance may have been the sense of urgency the symbol implied. When the pilot saw the X, he knew that danger was already very present and tended to pull back immediately. The other displays "eased" the pilot into the warning situation, enabling him to roll first and then pull.

Of the four displays, the Highway was the only roll-stabilized symbology. That is, the symbology rolled to conform with the horizon instead of with the aircraft. The other three were fixed-axis and required the pilot to keep track of roll separately from pitch via the roll indicator. Previous work related to attentional effects with superimposed symbology suggests that "the efficient processing of two information sources is only possible when they are part of the same perceptual object."[31] Since it rotated with the horizon, the Highway was a single perceptual object that incorporated both bank and pitch information. This may have allowed roll angle and altitude to be processed more efficiently. One can see from the chart that the Highway did indeed produce the least roll error, although it was not significantly different from the Chevrons or Mountain. Also, the Mountain performed slightly worse than the Chevrons. This coincides with comments from eight subjects who said the mountain symbol moving vertically gave the illusion that the aircraft was wings-level, when in fact it may have had significant bank. A better symbology would roll stabilize either the mountain icon or the y-axis along which it moves. One or both of these would likely improve the roll performance of this display. In the AFTI F-16, the HUD chevrons are roll-stabilized, and this should probably be incorporated in any chevron-type display.[10]

5.2.2 Altitude Maintenance

The main concern in comparing the four alerts was how much they helped with maintaining the target altitude. The pilot could not see the terrain during the recovery, and the

HUD altimeter showed barometric altitude. Thus, the PGCAS display provided the sole cue of AGL altitude. The pilots were instructed to maintain the target clearance height (500 ft AGL). Thus, altitude error can be defined as AGL Altitude - TCH. Time histories of altitude error for the four displays appear in Figure 5.3.

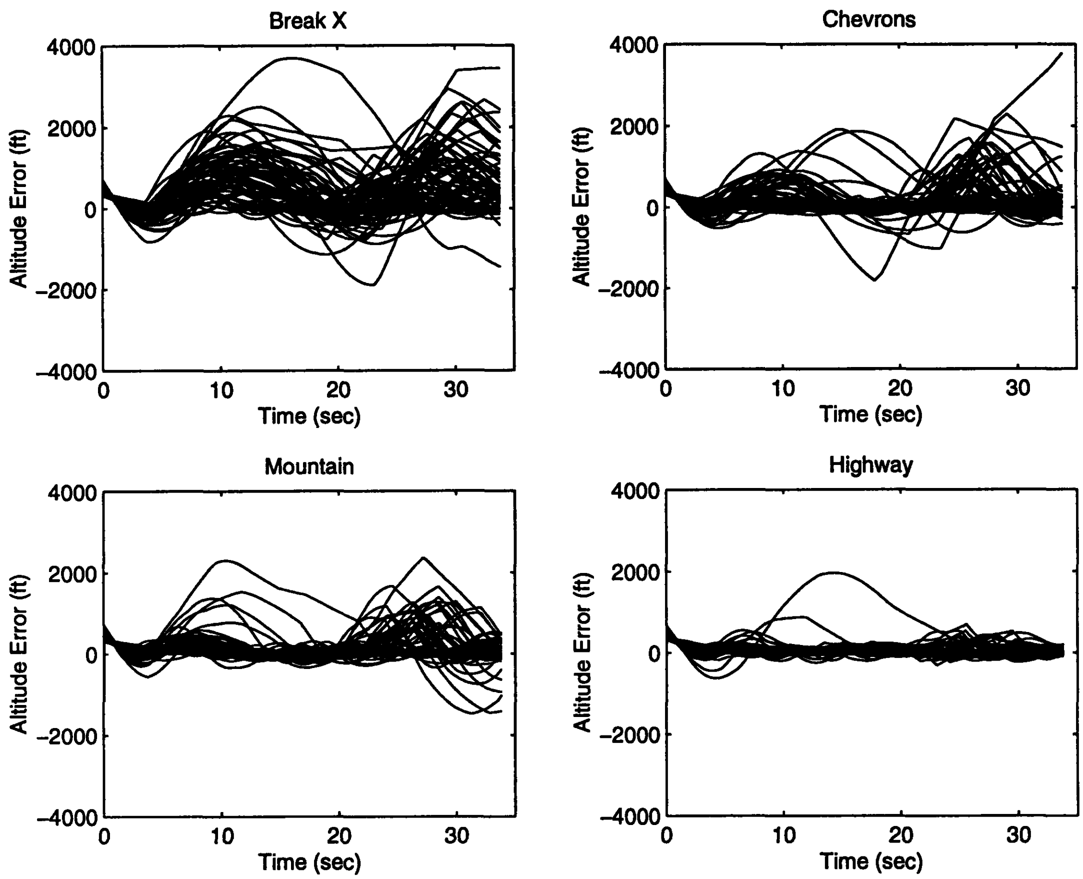


Figure 5.3: Altitude Error Histories (72 cases)

The figure shows progressively tighter grouping as one moves from Break-X to the Highway. This shows that pilots were better able to maintain the target altitude using the dynamic displays. Many of the Break-X trajectories show error up to 2000 ft, while the Chevrons and Mountain plots show only a few runs where this much error was reached. The Highway shows the least error, and only two trajectories lie outside the main group from -500 to +500 ft.

To better quantify the altitude performance from the four displays, one can examine the fraction of total time accumulated at each altitude. The four histograms shown in Figure 5.4 are cumulative over all of the pilots and over all of the terrain and entry conditions. Two vertical dashed lines, provided for reference on each plot, show the Safety Clearance Height and Warning Clearance Height at 250 ft and 750 ft respectively. The mean altitudes for the four displays are also shown. Negative altitudes have been lumped to produce the tall bar at zero, which represents the fraction of time the pilots spent in the crash condition. Altitudes above 2000 ft have also been lumped to produce the tall bar at 2000. The figure represents probability density for altitude, so the area under each curve is unity. Because the target altitude was 500 ft AGL, the ideal curve would have a tall spike at 500 with little area in the tails.

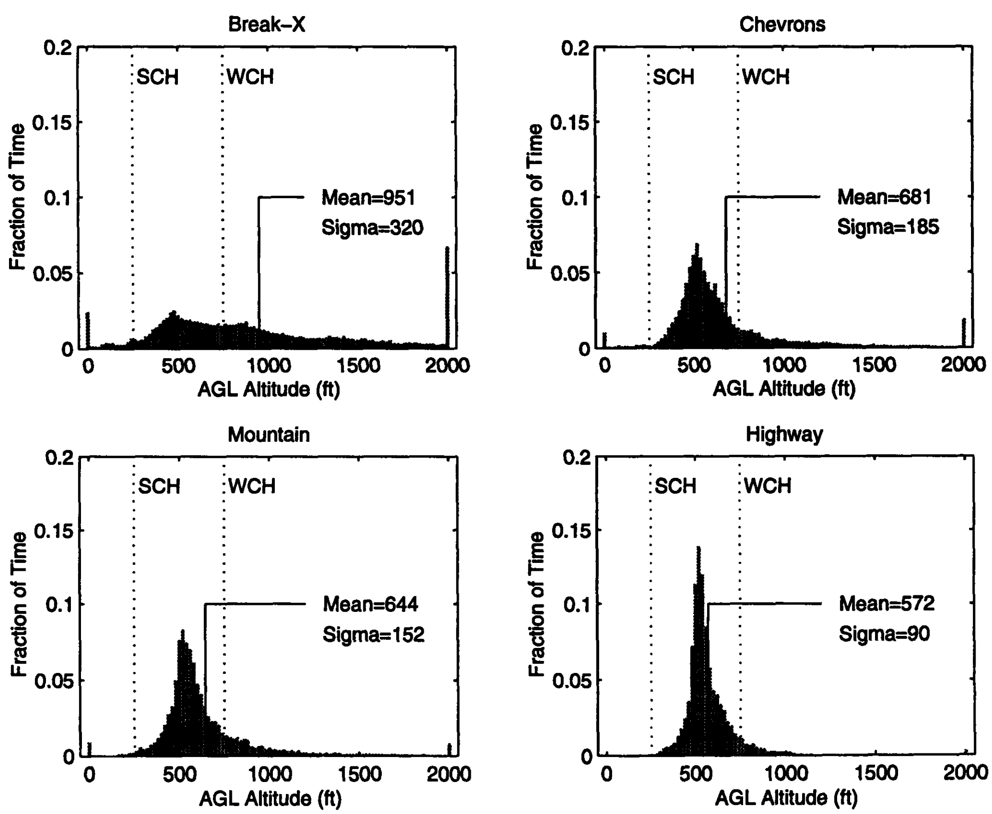


Figure 5.4: AGL Altitude Histogram (n = 72)

The curves are skewed to the right, toward higher altitudes. This is probably because pilots wanted to err to the high side, especially with the Break-X because it provided so little information. The Break-X produces a widely spread distribution with large area in the tails. The plot shows significant probability at and above 2000 ft AGL, well above the altitude where a SAM shootdown becomes likely. The fraction of time spent near the target altitude is quite small since the curve peaks at just over 2.5%. The Chevrons and Mountain produce better distributions, since the curves peak near 8% at the target altitude. The Mountain curve is taller and narrower than the Chevrons, denoting better performance. The Highway produces the most ideal histogram with a maximum near 15% and very little area in the tails. The amount of time spent outside the desired range of 250-750 ft is smaller than for any of the other displays. This shows that the Highway allowed the pilots to spend the most time near the target altitude.

The altitude range shown on the histogram can be divided into four bins: below the terrain, between the terrain and SCH, between the SCH and WCH, and above the WCH. Figure 5.5 shows the cumulative fraction of total time for each category. Crashed includes all negative altitudes and is the least desirable category. Negative altitudes were possible because the simulation continued to run even when the aircraft was below the terrain. This allowed multiple crashes during a single run for better display comparison. Next comes Terrain-to-SCH, which represents altitudes from 0 to 250 ft AGL. This category was considered dangerous but not fatal in the simulation. SCH-to-WCH is the altitude range in which the pilots were instructed to fly, 250 to 750 ft AGL. Finally, the area Above-WCH shows the fraction of time pilots exceeded the WCH (750 ft AGL). Time spent in this category meant risk of being targeted by ground threats.

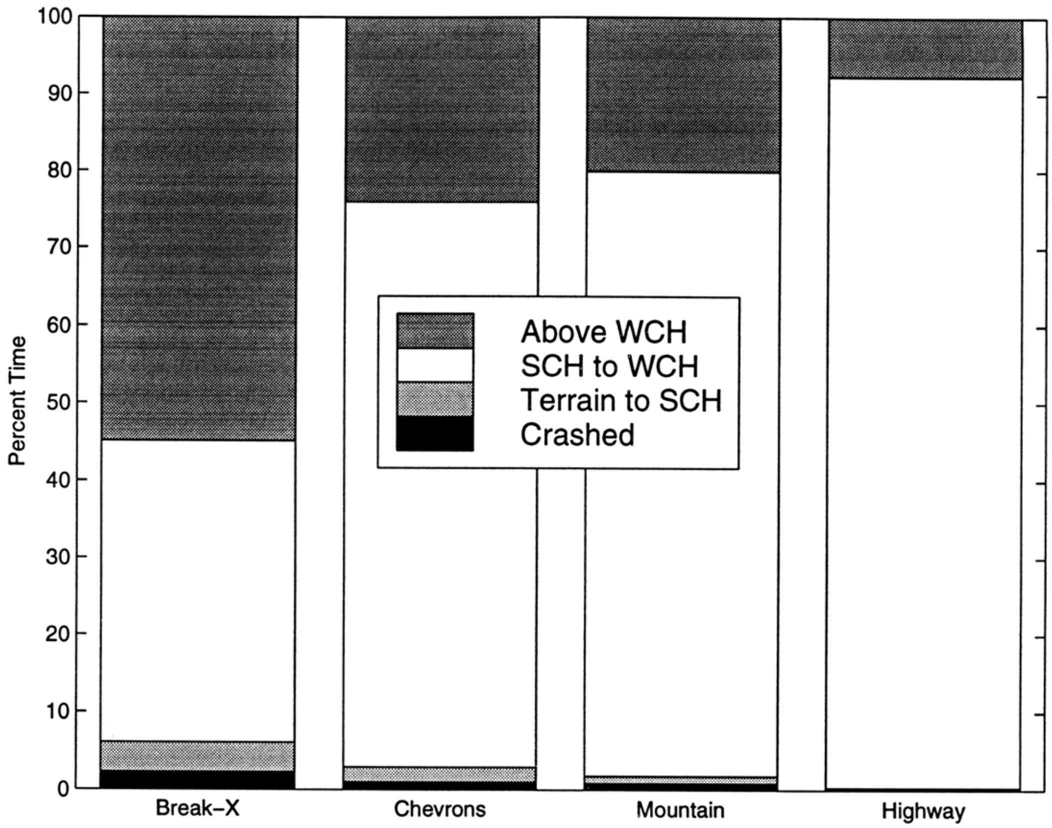


Figure 5.5: Time Spent in Altitude Categories (n = 72)

The Crashed category decreases steadily from Break-X to Highway, although it is relatively small for all four displays. The section representing Terrain-to-SCH also becomes smaller across the four displays, meaning that pilots spent less time in the dangerous region below the Safety Clearance Height. The area showing SCH-to-WCH grows steadily, which is consistent with the histogram analysis above and means that pilots spent more time within the accepted altitudes. Since the above-WCH category lessens across the displays, pilots tended to exceed the WCH less often using the more informative displays. This allowed them to remain in the acceptable altitude range more consistently by using the display guidance to level off.

The Crashed category is very important since this is the most catastrophic of all possible outcomes. Thus, it has been expanded in Figure 5.6 to allow better comparison.

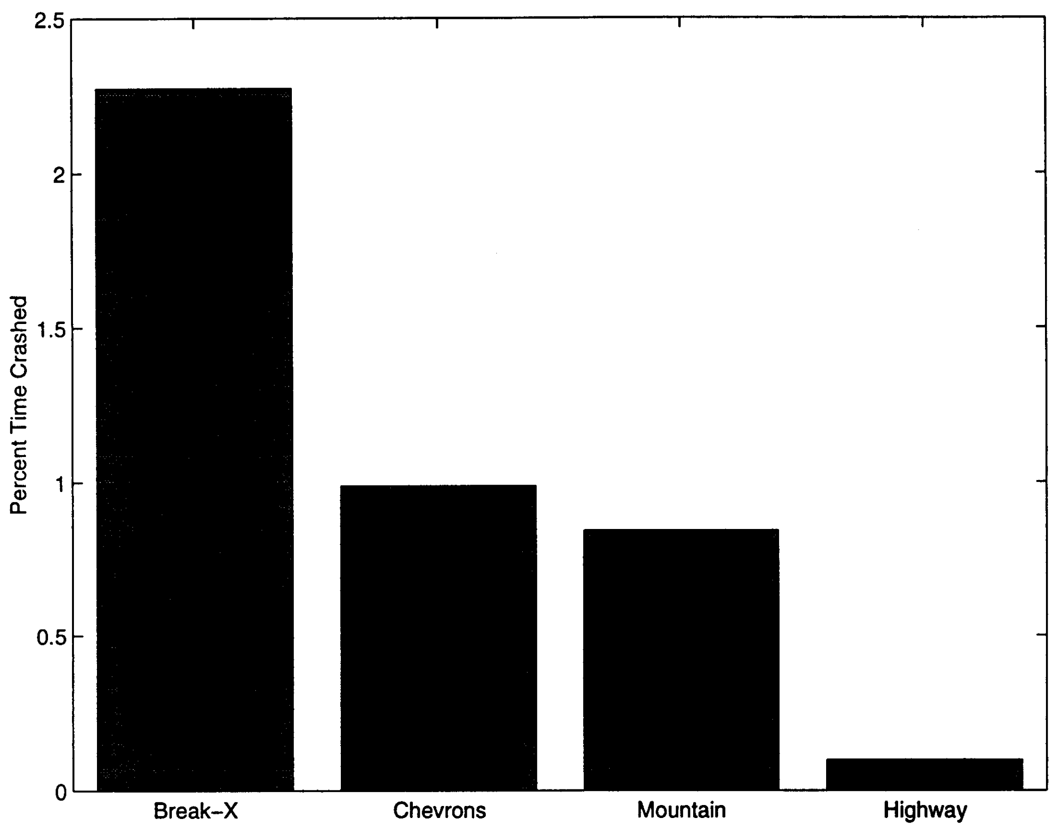


Figure 5.6: Time Spent in Crash Condition (n = 72)

A significant difference exists between all of the displays except between the Chevrons and Mountain. The Chevrons and Mountain presented similar information, so it is expected that they would produce comparable results. The Mountain gave additional guidance as the aircraft descended from the SCH to the terrain by spreading across the top of the screen, while the Chevrons formed an X at the SCH and remained that way until a collision. This may have contributed to the difference that does exist, although it is not statistically significant. The

Highway produced the least time in the crash condition, probably because the pilots were more aware of the terrain ahead and could implement control inputs earlier.

Another metric which can be used to determine the effectiveness of the displays in preventing crashes is the discrete number of crashes, defined by the aircraft's altitude going from positive to negative. This is slightly different than the time spent below the terrain because a pilot who was more aware of his altitude should have recovered earlier and spent less time below the terrain during each crash. Figure 5.7 compares the average number of crashes per run.

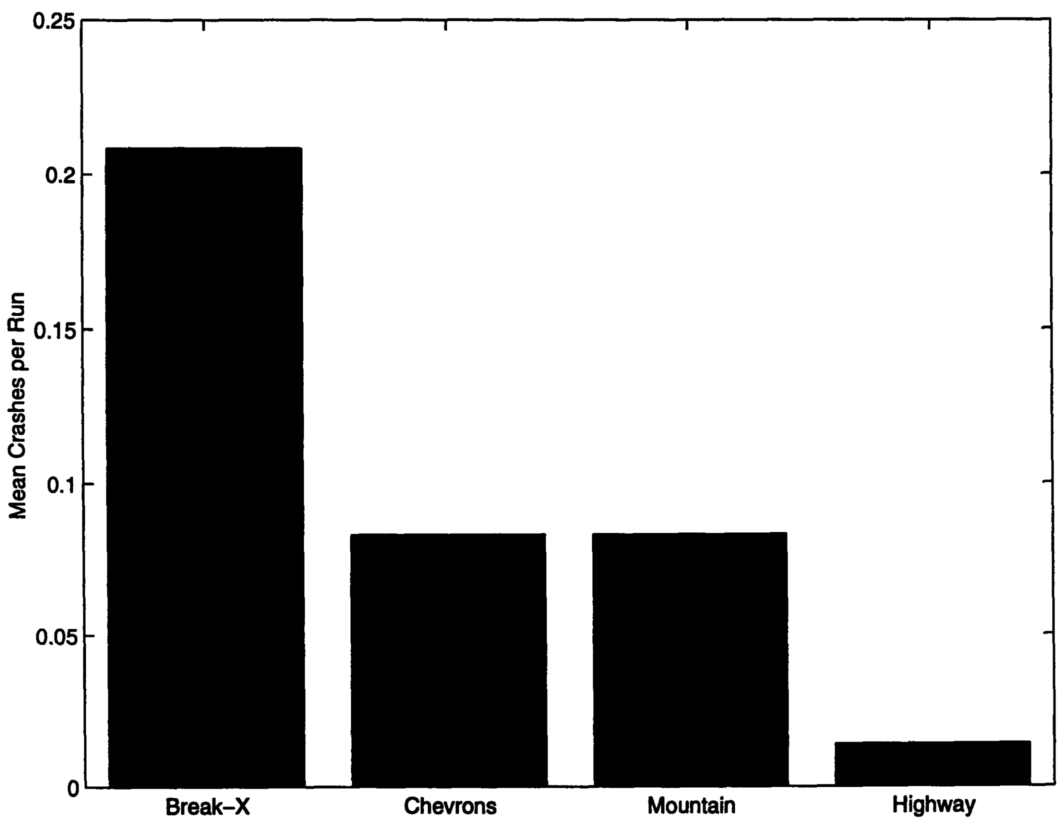


Figure 5.7: Number of Crashes per Run (n = 72)

Because these data were produced by counting crashes, the F-test for two counts based on the Poisson distribution applies.[30] This test does not determine a critical mean difference, but can determine whether a significant difference exists between each pair of displays. All of the differences are significant except for the one between the Chevrons and Mountain (95% confidence). Again, the Highway outperformed the Chevrons and Mountain which in turn did better than the Break-X. Note the similarity between Figure 5.6 and Figure 5.7. Since both plots show the same relative bar heights and trends, it is reasonable to infer that both "time crashed" and "number of crashes" are similar indicators of display performance.

Another item of great concern in this project was to determine how well the various displays allowed the pilot to level off after the initial pull-up. This would not apply to civilian aircraft because they generally do not have a tactical ceiling. For military flying, though, it could mean the difference between preserving and losing the stealth which terrain masking provides. One way to compare level-off performance is to see how many times the pilots penetrated the WCH, below which they were instructed to stay. Figure 5.8 compares the number of WCH busts, and all of the differences are significant except for between the Chevrons and Mountain.

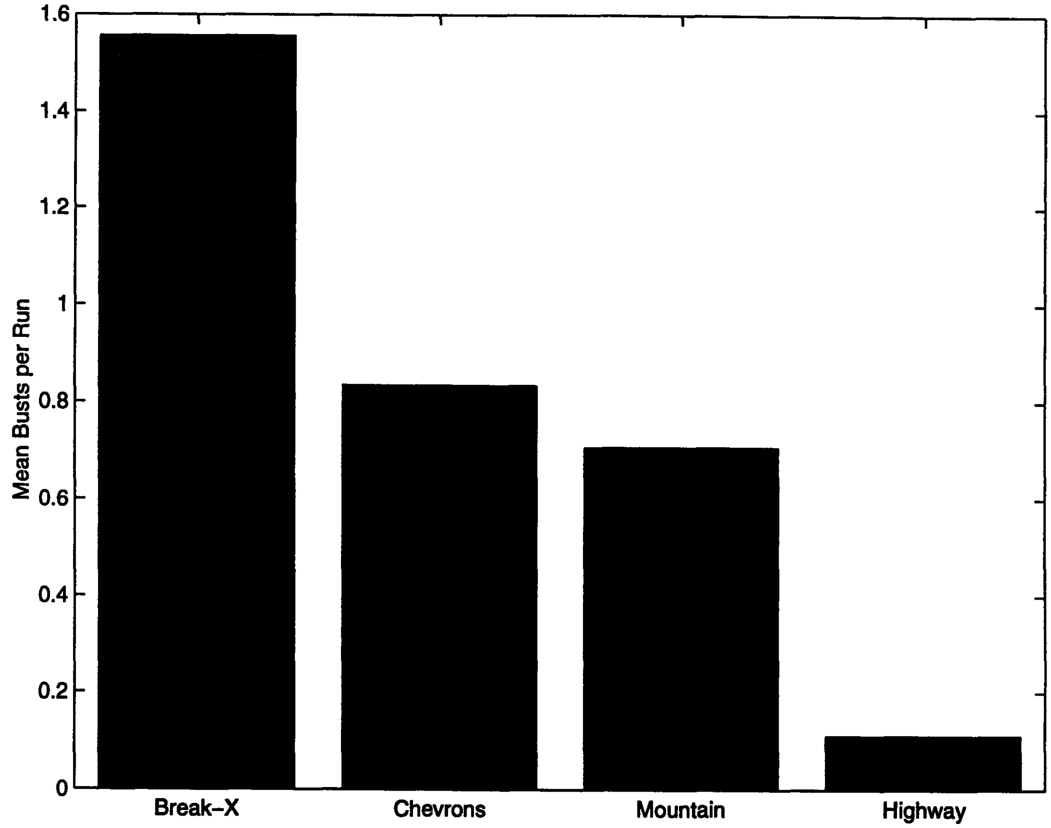


Figure 5.8: Number of Altitude Busts per Run (n = 72)

The Highway produced the least ceiling penetrations, followed by the Chevrons and Mountain. The Break-X was significantly worse in this area than the other three alerts; the average was more than one penetration during each run. The primary reason was probably the binary nature of the Break-X. When it disappeared, the pilots theoretically should have leveled off. They often continued to climb, though, because they wanted to be sure the "X" did not reappear. The tension between penetrating the ceiling and receiving another alert was noticeable, and often the pilots chose to penetrate the WCH rather than receive another Break-X. The other alerts provided feedback as the pilots climbed, and they were able to level off quickly at the TCH because the symbology remained on the HUD.

5.2.3 Altitude Trends

There are several ways to quantify altitude error for analysis. One method simply averages the errors at all of the timesteps to produce a mean altitude error for each run. These errors were averaged between runs and subjects to produce Figure 5.9. One must remember that a positive error at one timestep tends to cancel a negative error at another, reducing the overall sum. Thus, averaging is most useful to see whether the pilots tended high or low.

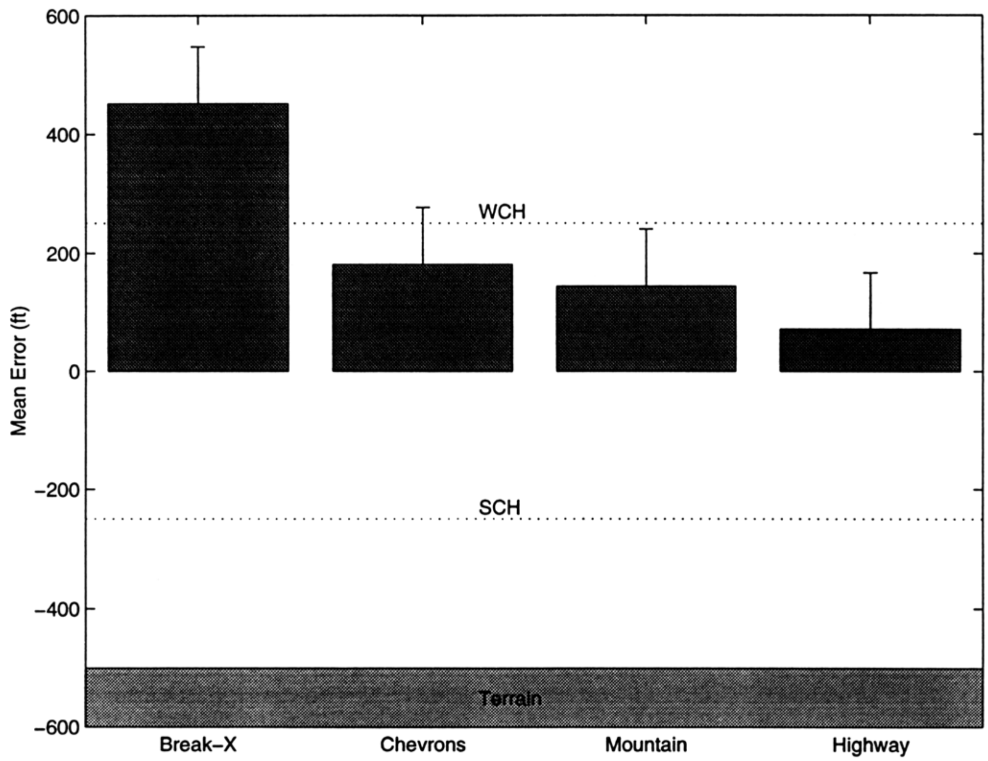


Figure 5.9: Mean Altitude Error (n = 72)

The figure shows that the pilots tended to fly progressively lower (closer to the target altitude) as one moves across the displays from left to right. The pilots intentionally or inadvertently tended to err high with the Break-X. This probably means they flew more conservatively due to the lack of information present. They were more confident with the more informative dynamic displays since they provided more knowledge of the terrain. This allowed the subjects to fly lower because they had less fear of CFIT. The Highway produced the lowest trends, and the pilots felt the most confident using it.

The magnitudes of the averaged errors are not necessarily comparable because positive and negative errors cancel one another. The magnitudes can be compared, though, by averaging the absolute value of error instead of the error itself. The resulting data is shown in Figure 5.10.

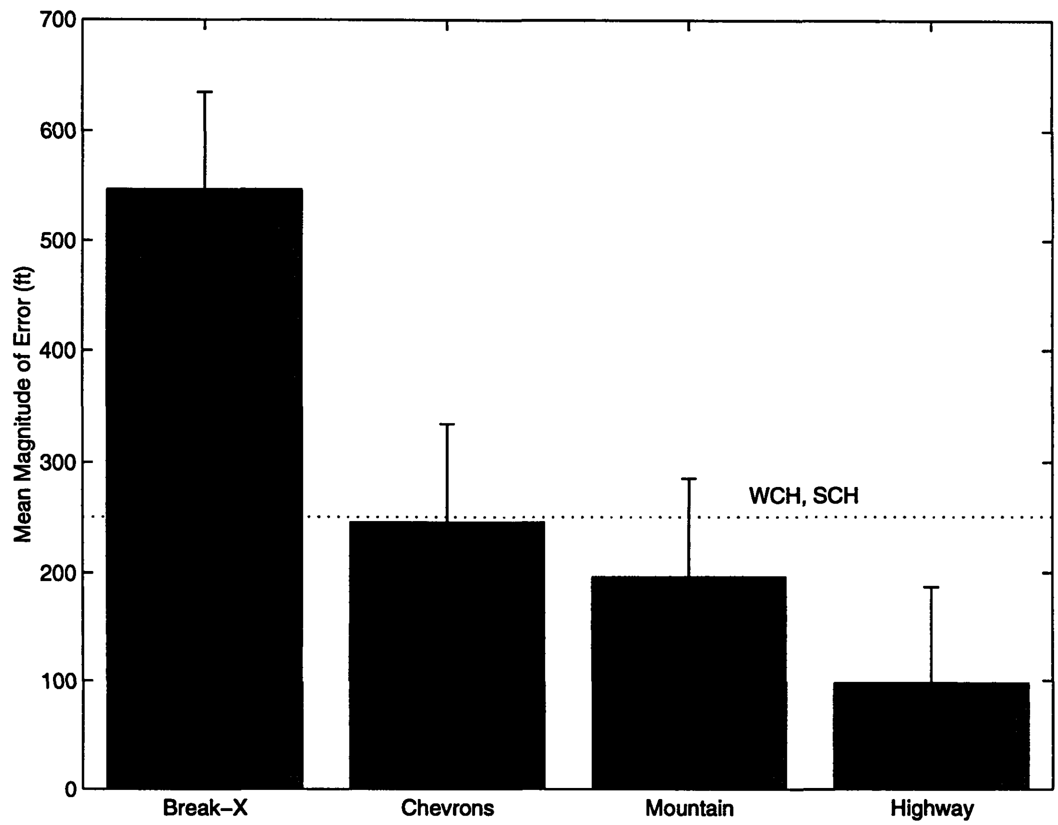


Figure 5.10: Mean Magnitude of Altitude Error (n = 72)

When the absolute value of the error is used as a metric, the displays again produce progressively less error across the four displays. The error bars show the least significant difference, so the other three displays performed significantly better than the Break-X. The Highway produced significantly less error than the other displays, and the Mountain was better than the Chevrons although the difference is not significant. The dashed line shows the location of the Warning Clearance Height and the Safety Clearance Height, respectively 250 ft above and below the TCH. These were the limits within which the subjects were instructed to stay. One can see that the Break-X error is well outside the bound, meaning that the subjects as a group did not achieve the goal stated. The Chevron error lies just inside the bound, while the Mountain and Highway errors are well below the line. This means that all three dynamic displays enabled the pilots on average to achieve the altitude following goal.

5.2.4 Terrain Effects

Runs using the two different terrain types can be separated as in Figure 5.11. This allows comparison of the four displays over smooth and rugged terrain. The performance metric shown on this chart is RMS altitude error, which is similar to the mean error magnitude. The difference is that the square root was taken after dividing by the number of cases. This means large errors were weighted more heavily than small errors, and this is appropriate since danger increases rapidly with altitude error.

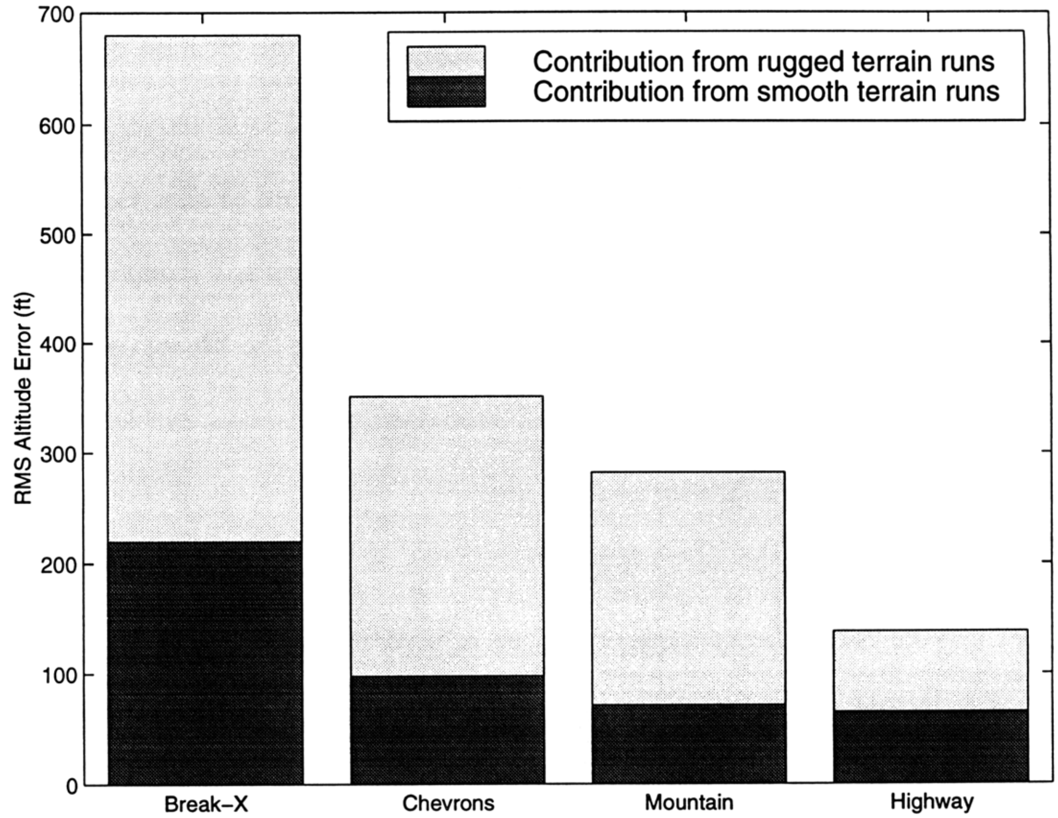


Figure 5.11: Terrain Effects on Altitude Error (n = 72)

The figure shows that the three continuous displays produce similar performance over smooth terrain; all of them perform better than the Break-X. Over rugged terrain, though, a significant difference exists between the three displays. The Highway is significantly better than the Mountain, which is in turn better than the Chevrons. This is not surprising, because following rugged terrain demands more control input from the pilot. If the terrain had been completely flat, the pilot could theoretically have noted the altitude where the Break-X appears and leveled off just above it without even using the symbology. But over rugged terrain, a display must provide more active guidance for accurate terrain masking. This guidance was present in the dynamic displays. The Highway performed significantly better than the other displays over rugged terrain.

The predictive surface enabled pilots to evaluate terrain features ahead of the aircraft before reaching them. Thus, their corrections were immediate and appropriate instead of lagging behind the symbology.

5.2.5 Dive Angle Effects

When the alerts occurred, pilots were near one of three dive angles: 5°, 15°, or 25°. The purpose for testing differing flight path angles was to see whether steeper angles would produce more altitude error. Figure 5.12 shows the results with smooth and rugged terrain runs separated.

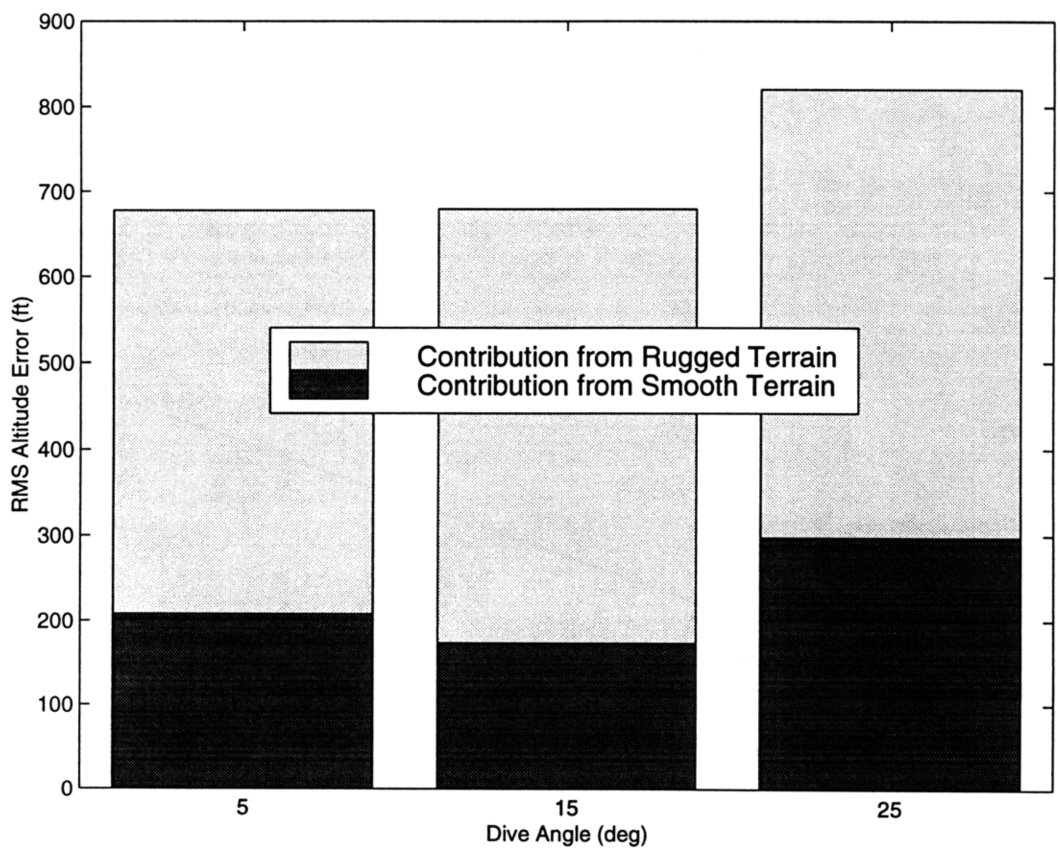


Figure 5.12: Initial Dive Angle Effects on Altitude Error (n = 72)

The figure shows that a 25° dive angle produced more altitude error than 5° or 15°. Aircraft diving more steeply took longer during the initial recovery to stabilize near the TCH, which may have contributed to the larger error. More oscillation about the TCH was expected for steeper entries because pilots would tend to overshoot the TCH initially, especially using the Break-X. The other three displays provided some advance warning so the pilot could anticipate the recovery and time it to achieve the TCH more quickly. Initial roll angle was not found to have any significant effects on altitude performance.

5.2.6 Age Effects

It was wondered whether the age of the subjects would have any effect on performance. This was not just for curiosity, but also related to how well pilots might adapt to a new PGCAS display. Figure 5.13 is a plot of RMS altitude error versus age, including a best-fit linear regression.

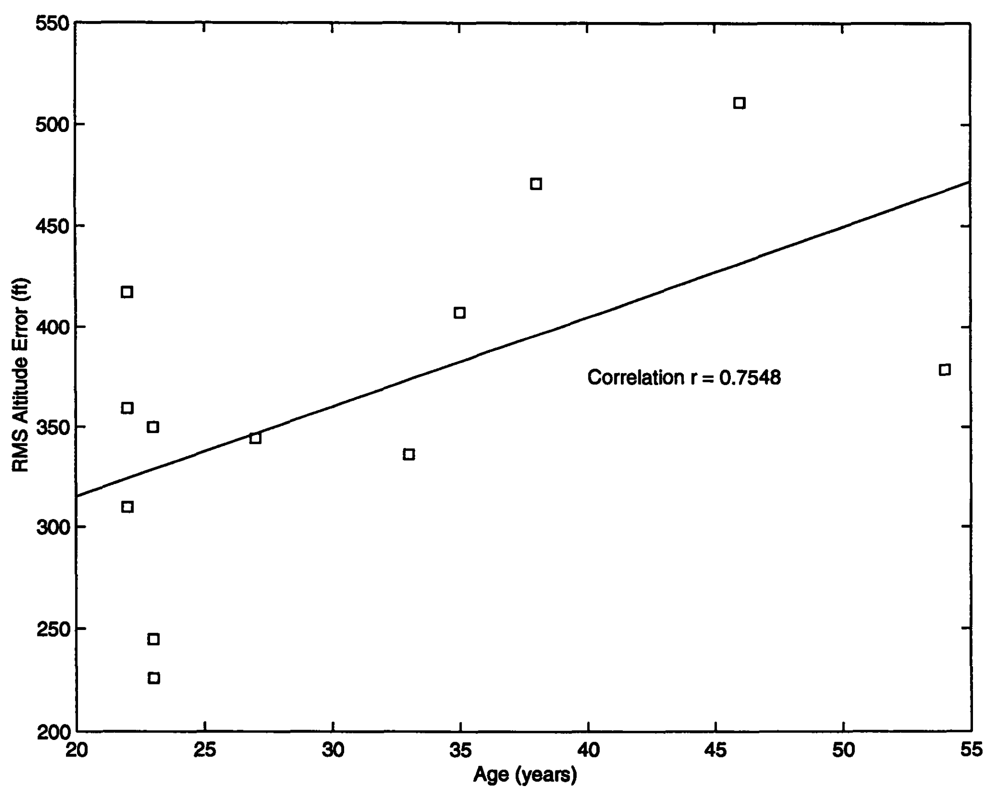


Figure 5.13: Age Effects on Altitude Error (n = 12)

One can see that age and performance in this experiment were correlated. A t-test for correlation determined with 95% confidence that the correlation was significant. There are several reasons why older subjects may have followed the TCH less accurately. First, reflexes and hand-eye coordination are known to slow down as one gets older. Second, the older pilots learned to fly when HUDs were less common, and they lack the video game experience that is actually valuable when flying this type of simulator. Finally, they may have had experience with traditional GCAS and had trouble adapting to new symbology, while the younger pilots had never used GCAS and thus had no paradigms to break. If the third reason was substantial in causing the performance decrease, it would suggest that any new symbology must be implemented carefully with adequate training to ensure pilots learn to use it well.

5.2.7 Effort Measurement

One of the objectives of the experiment was to examine the pilot effort level required to follow the various symbologies. A large amount of pilot effort suggests that an advanced PGCAS display is inefficient and perhaps uncomfortable to use. It may also be unnatural, requiring constant inputs and corrections to null out previous errors. One measure of pilot effort is longitudinal stick position. Large oscillating stick inputs suggest that the pilot was over-compensating and was thus kept quite busy with the altitude tracking task. If fewer stick inputs were recorded, the pilot was better able to judge the correction needed to null a given error. Figure 5.14 shows the RMS value for longitudinal stick position, averaged between runs and between subjects.

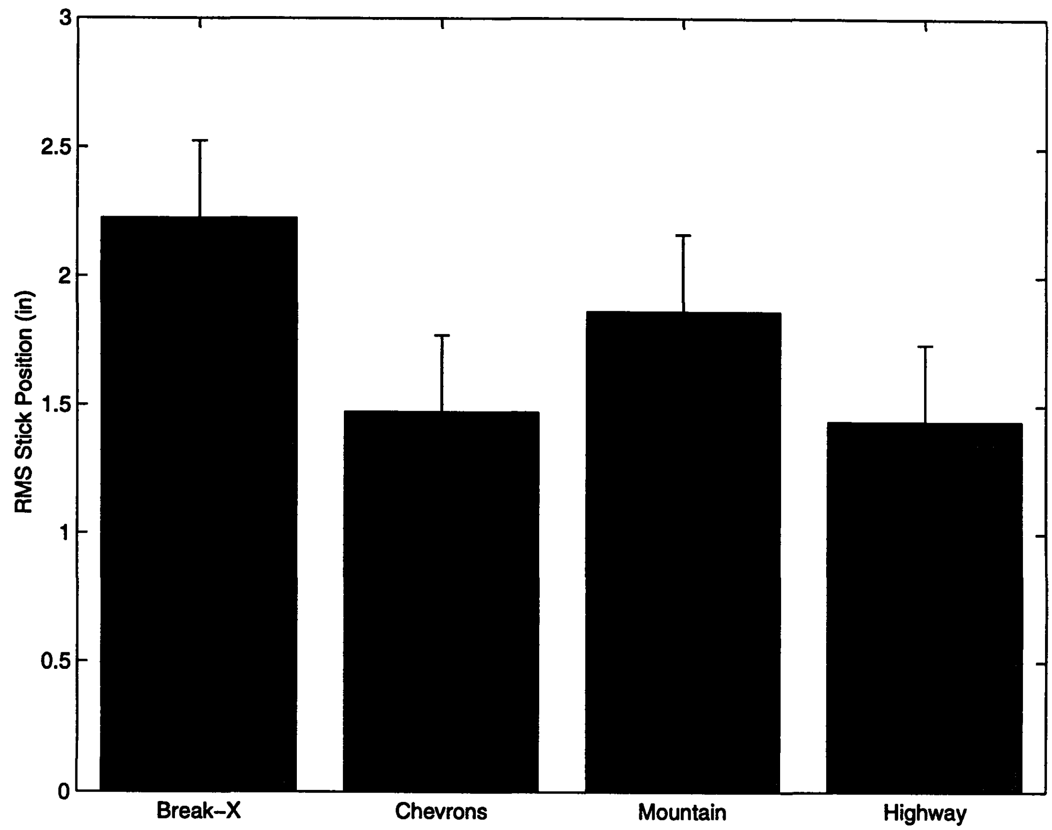


Figure 5.14: RMS Longitudinal Stick Position (n = 72)

One can see that the Highway produced the least longitudinal stick input, although it was not significantly better than the Chevrons. The Break-X again performed worse than the other three displays, because most pilots made large inputs as they attempted to fly just above the altitude where the X would appear. The significant difference between the Chevrons and Mountain coincides with pilot comments that the Mountain appeared to move faster and therefore required more effort to follow. In truth, the two symbols moved at the same velocity, but the Mountain moved across a vertical space while the Chevrons moved horizontally. To the human eye, vertical lines and spaces appear larger than equal-length horizontal lines and spaces.[32] Since the Mountain moved across an apparently larger space in equal time, it may have seemed faster.

Interestingly, the pilots had a harder time following the Mountain but performed better using it. This suggests a trade-off between effort level and performance for these two displays.

5.3 Subject Comments

The twelve subjects were interviewed orally after using each display, and the experimenter recorded their responses. The responses appear in Appendix D.

5.3.1 Strategies and Preferences

The first question asked what strategies the pilots developed for following the alerts and which they felt worked the best. According to their responses and the recorded altitude profiles, the Break-X produced a great deal of oscillation. Generally, the pilot would pull hard until the Break-X disappeared. He would then lower the nose to -10° or -20° flightpath angle and wait for the symbol to appear again. All agreed that the Break-X wastes energy and effort and does not provide much feedback. The Break-X was called effective for alerting the pilot, but very ineffective for terrain following and terrain avoidance. One subject thought that the Break-X was better for getting the pilot's attention than the other alerts. The pilots agreed that the Break-X was the poorest alert for this task because of its binary nature. They were in danger of ground collision with the X present, and in possible danger of SAM shootdown with the X absent; no state was considered safe.

The main comment about the Chevrons was the ambiguity arising from the horizontal orientation of the axes. Eight subjects commented that the horizontal movement of the chevrons did not correspond to the vertical motion of the outside world. For some people, this caused confusion under duress about which way the chevrons were desired to move. Quick movement of the chevrons in either direction often caused the pilots to pitch upward, even if the chevrons had moved outward (toward safety). This reverse-control is very dangerous and difficult to overcome once it occurs. Several subjects noted that they only needed one chevron because the display was symmetric across the vertical axis and both chevrons gave the same information. This suggests using a single symbol such as the Mountain. The pilots appreciated the fact that the Chevrons moved out of the FOV as danger decreased. Thus, they could be seen peripherally without interfering with the other HUD symbology. But when danger was present, they moved to center-HUD and attracted attention.

The pilots liked the vertical motion of the Mountain because of the way it corresponded to the outside world. Some commented that it implied the shape of the terrain, which was not necessarily true. When compared with the Highway, the consensus was that the Mountain moved more quickly with less warning. Thus, people found it hard to keep the aircraft reference symbol near the top of the mountain in rugged terrain. They also commented that the Mountain would drop off the screen above the WCH, leaving no indication of danger when flying too high. If danger still exists, it should be shown by the display. Some pilots thought that the mountain icon spreading across the top of the HUD appeared to be less urgent than a central X. Others commented that the Break-X cluttered the center of the HUD because it didn't move. This illustrates the trade-off between urgency and clutter that must be addressed when designing this type of display.

Overall, the pilots felt the most comfortable performing the altitude tracking task with the Highway because of its predictive nature. One positive aspect was its correspondence to the outside world, which allows one to think of it as a physical object. Pilots tended to fly the FPM along the surface far ahead of the aircraft, noting their current altitude by the location of the nearer bars. Eight subjects said that they could anticipate the terrain ahead much better using the Highway, allowing them to time control inputs to follow the terrain more accurately. Among the suggestions for improving the display were to add exponential scaling, to change the post spacing with the ruggedness of the terrain, and to thin out the bars to demand less of the HUD drawing computer.

5.3.2 Rolling Tendency

The second question asked how the pilots' tendency to roll wings-level changed between the four displays. Because the Break-X was stationary, it provided no bank indication and the subjects agreed that it did not hinder or help with rolling to wings-level. The Chevrons moved, but they were not intended to represent objects in the outside world. Thus, they were still considered icons, and the subjects seemed able to keep roll motion separate from the pitching demanded by the chevrons. The Mountain, however, had a physical analogue because of its vertical motion. Thus, all of the pilots agreed that it should be roll-stabilized. Some found it to be a false indicator of wings-level because it appeared level even if the aircraft was banked. Overwhelmingly, the Highway was preferred for keeping the pilot aware of bank angle. Pilots commented that it is natural to view the symbology vertically, and one automatically rolls to establish wings-level so that the surface moves up and down. This corresponds to the analytical data, which showed the Highway producing the least RMS roll error.

5.3.3 Qualitative Ranking

The third question asked the subjects to qualitatively rank the four alerts and provide reasons. All of the subjects preferred the Highway overall. Among its listed advantages were good roll indications, important predictive information, and improved SA. About half of the subjects ranked the Chevrons second, while the others ranked it third. Those who preferred the Mountain to the Chevrons appreciated the way the mountain symbol's motion corresponded to the terrain. They called the Chevron display "counterintuitive" because axis of motion was not aligned with the physical world. All of the subjects ranked the Break-X last for the tasks they performed in this experiment. It was considered effective for getting the pilot's attention and prompting the initial pullup but ineffective for providing roll information and guidance during the remainder of the recovery.

5.3.4 Comments on Simulation

The last question asked for general comments on the simulation. All subjects felt they had adequate training time and sufficient rest between tasks. Most claimed they were not expecting the alert when it arrived, which meant the goal of surprise was achieved. Some felt they improved across the six runs with a given display or across the four displays. This was primarily due to improved knowledge of the aircraft dynamics. Several improvements were suggested for the various displays, but the simulation itself was well-accepted.

5.4 Analytical Hierarchy Process

The subjective comparison ratings were used with the Analytical Hierarchy Process (AHP) to obtain overall display preferences for each subject in terms of percentages.[33] The first question asked the subjects to compare how much the four displays helped them during the initial pull-up. This is often the most crucial part of the recovery since the aircraft is in immediate danger of collision. The subjects were asked to separate the initial pull-up from the remainder of the recovery, and the results are shown in Figure 5.15.

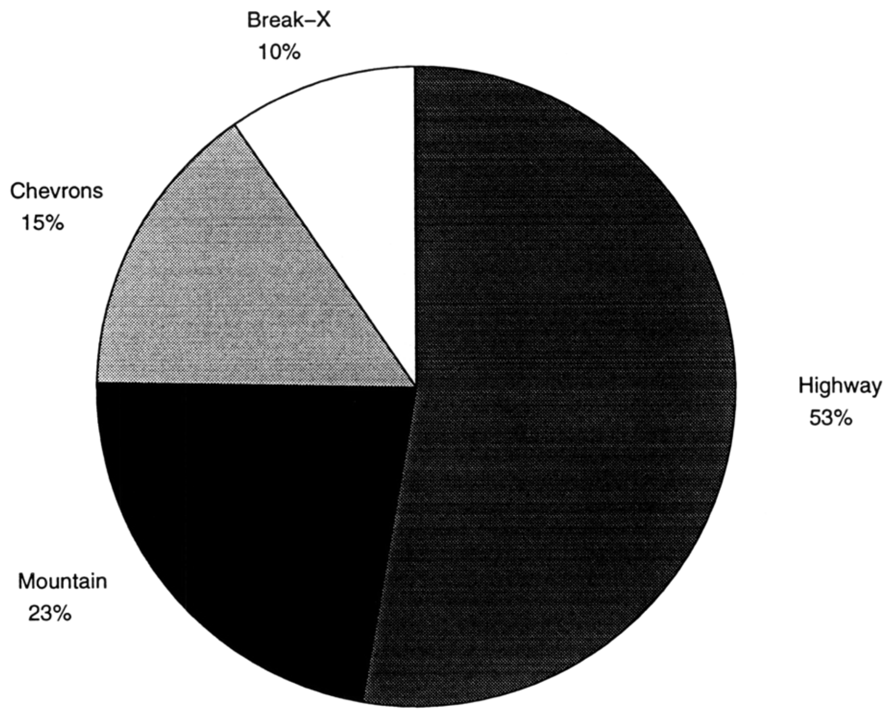


Figure 5.15: Initial Pull-up Usefulness (n = 12)

As shown by the pie chart, the subjects considered the Highway the most useful, followed by the Mountain, the Chevrons, and the Break-X. The Highway was preferred about twice as much as the Mountain, three times as much as the Chevrons, and five times as much as the Break-X. The Break-X appeared in the center of the pilot's field of view and was the only HUD symbology that did not move. This made it stand out from other HUD objects and alerted the pilot of impending danger. Because it was binary, though, it gave no indication of how much danger existed; only that it did exist. The second question asked how much the four displays helped with maintaining the Target Clearance Height after the initial pull-up. This was to evaluate the terrain-tracking portion of the task, and the results are shown in Figure 5.16

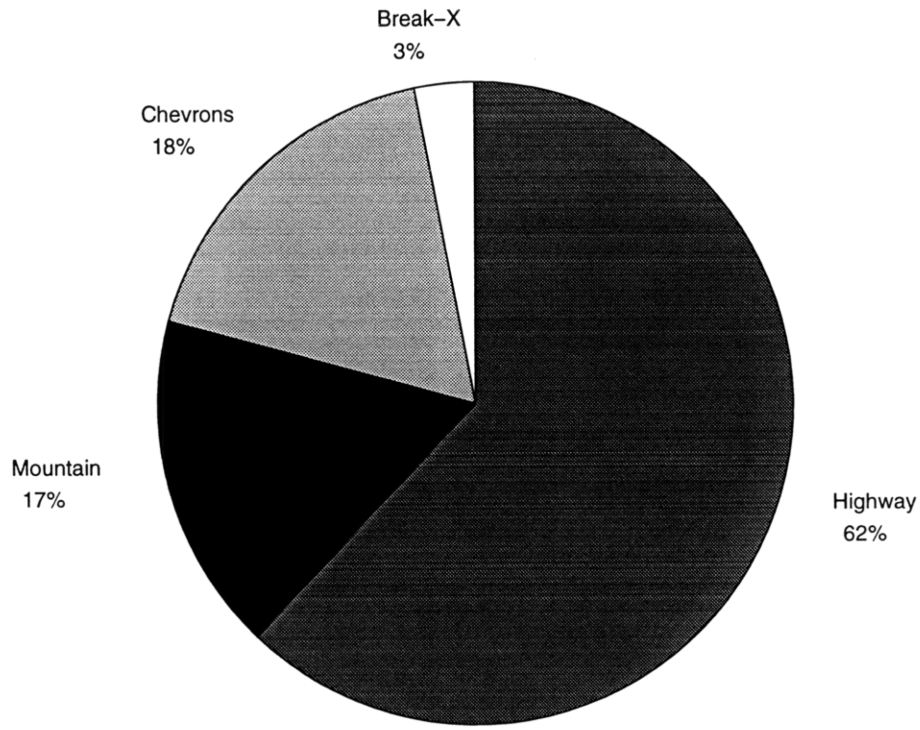


Figure 5.16: Terrain Following Usefulness (n = 12)

The figure shows the same order of preference as the first question, but the Break-X falls further behind the other displays. This is likely because it was effective initially for getting the pilot's attention, but it became ineffective as a terrain following cue. In Figure 5.17, one can see the results from the third question, which asked the subjects to rate their overall preference of the four displays.

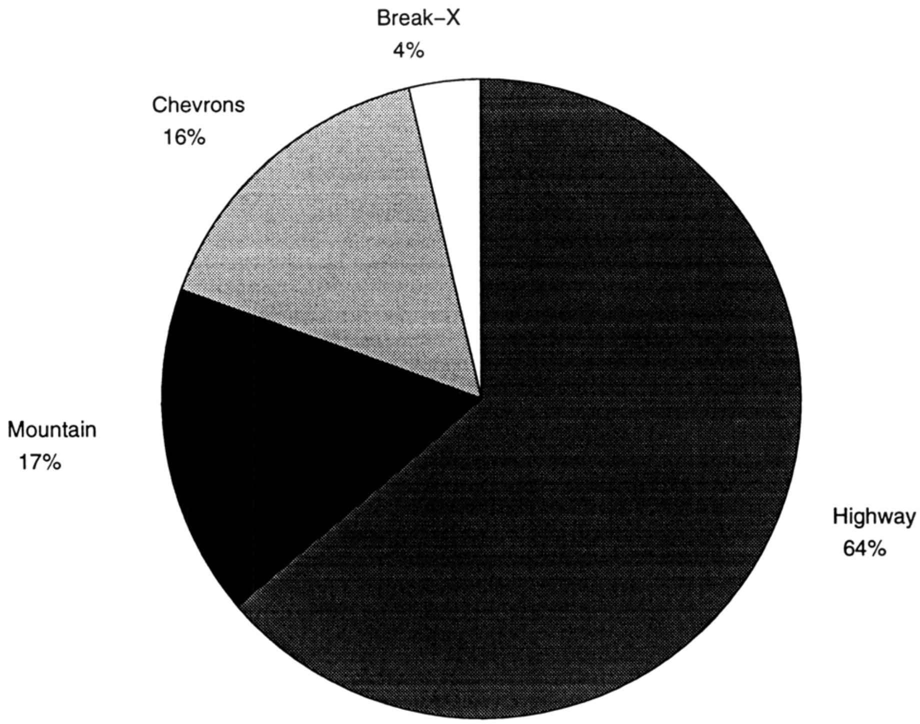


Figure 5.17: Overall Display Preference (n = 12)

Again, the Break-X is far behind the other three displays. It lacks the terrain closure-rate information that is present in the others, making it a very uncomfortable display to use for this task. The Chevrons and Mountain were ranked approximately evenly, although each subject tended to prefer one or the other. The Highway was preferred about three times as much as either of them, and its primary advantage was that it showed upcoming terrain.

6 Conclusions and Recommendations

Four advanced ground collision avoidance displays were tested using a fixed-base T-38 simulator with a projection screen and simulated HUD. Twelve subjects flew through a series of PGCAS situations in zero visibility using each display. For about 30 seconds after the alert, they attempted to maintain a set AGL altitude, clear of the terrain but below ground radar threats.

The Break-X display was similar to the standard military alert except that it remained on the screen until the aircraft was recovered to safety. The Chevron display slid horizontally inward as danger increased, forming an X identical to the break-X. The Mountain display utilized a terrain icon which moved upward in the HUD as danger increased, mimicking the motion of the terrain outside. The Highway display was a preview depiction of a perspective elevated surface at the desired altitude.

6.1 Conclusions

6.1.1 Break-X

The experimental results show that the Break-X display performed significantly worse than the other three displays. First, it produced more RMS roll error than any of the other displays. It was immediately urgent, so pilots tended to pull immediately instead of first evaluating the aircraft attitude and rolling appropriately. Second, the Break-X provided little security and produced poor altitude following. When given a Break-X, subjects spent significant time outside the bounds within which they were instructed to fly. Rough terrain further increased the performance gap between the Break-X and the three dynamic displays. The Break-X allowed more than twice as many crashes and Warning Clearance Height (WCH) penetrations as the next best display. Third, pilot effort was the highest with the Break-X. Subjectively, it placed a distant last behind the other three displays. The subjects considered it effective for alerting the pilot but very impractical for a terrain-following, terrain-avoidance (TF/TA) task like the one performed here.

6.1.2 Chevrons

The Chevron display was significantly better than the Break-X in all areas. It produced much less roll error and permitted more accurate altitude tracking. Using the Chevrons, pilots spent about 70% of the flight time between the desired clearance heights, compared to 40% for the Break-X. The Chevron display allowed only half as many crashes and ceiling penetrations as the Break-X, meaning it is much better for terrain avoidance and leveling off after the initial pull-up. Average altitude error was only half what the pilots accumulated when given the Break-X. The Chevrons produced less stick movement than the Break-X or Mountain. Their horizontal motion may have appeared slower than the vertical Mountain motion, so they prompted fewer error corrections. About half the subjects preferred the Chevrons to the Mountain, while the others ranked the Mountain higher. The chief complaint about the Chevrons was the fact that their horizontal motion had no physical meaning in the real world. This sometimes led to ambiguity and even reverse-control.

6.1.3 Mountain

The Mountain produced slightly more roll error than the Chevrons, probably because it provided the false illusion of wings-level. This led to entire recoveries performed at a significant bank angle and therefore larger RMS roll errors. This problem would be alleviated with roll-stabilization, that is, rotating the icon to conform with the horizon. Compared to the Chevrons, the Mountain resulted in similar but slightly better altitude performance. Pilots spent slightly more time between the desired clearance heights and less time above the tactical ceiling.

However, they crashed about as many times using the Mountain as they did using the Chevrons. Interestingly, the improved altitude performance came at the cost of significantly more stick movement. A possible cause is that the Mountain was perceived to move more quickly than the Chevrons. The primary objection to the Mountain was that it was not horizontally stabilized, so it provided the false illusion of wings-level.

6.1.4 Highway

The Highway outperformed the other three displays in every category. It produced the least roll error, although not significantly less than the Mountain or Chevrons. This is probably because it was roll-stabilized; meaning the pilots could draw both roll and flight path information from the single HUD object. The Highway allowed the most flight time within the desired altitude layer; about 90% compared to 80% for the Mountain and 70% for the Chevrons. The Highway resulted in the fewest crashes and ceiling busts, and it produced the least stick movement although not significantly less than the Chevrons. The pilots made timelier, more appropriate inputs with the predictive information offered by the perspective surface. The Highway and Mountain were nearly equal over smooth terrain, but the Highway was much better over rough terrain. Subjectively, the Highway was rated as the most desirable display for the initial roll, the pull-up, and the remainder of the recovery.

6.2 Recommendations

6.2.1 Future Work

Several pieces of follow-on research would further validate these results and continue progress toward a better PGCAS display. First, the conclusions obtained from this experiment suggest that a dynamic display providing feedback would better serve the flying community than the static break-X. Thus, further research should concentrate on dynamic PGCAS symbology and ways of implementing motion in the HUD. Three candidates were suggested here, and there are numerous other ways of showing terrain closure rate to the pilot and helping him determine when the aircraft is recovered to safety.

Second, the displays discussed could be improved and expanded upon to help determine PGCAS alert requirements. The chevrons should be roll-stabilized to provide concurrent bank information. Because the two chevrons moved symmetrically, there is a possibility that only one is needed. This would produce less HUD clutter, allowing more space for other symbology. With one or both chevrons, the pilot must be given a definite indication whether danger is increasing or decreasing. This would help prevent the ambiguity and reverse-control that sometimes occurred using the Chevrons in this experiment.

A vertically moving display like the Mountain naturally reduces the ambiguity. It has physical meaning attached to the outside world, and pilots are conditioned to see rising terrain as a sign of danger. The display should use a roll-stabilized icon or move the icon along a roll-stabilized axis. An appropriate gain must be chosen for a Chevrons- or Mountain-type display so that the symbology moves quickly enough to attract attention but slowly enough to be anticipated and followed. The shape of the mountain icon could change to show the characteristics of the terrain ahead, much like the kinematic horizon discussed earlier. If this is impossible, it should maintain a generic shape that does not imply real terrain shaped the same way.

To allow even better anticipation, a preview display like the Highway should be used. One possible improvement would be to scale vertical movement exponentially instead of linearly. Although this would prevent the display from being completely conformal, it would help prevent very rapid motion toward the extremes of the HUD and make the display less distracting. Also, the post spacing could be reduced or adapted to the terrain type in order to reduce the number of lines. A tunnel display might better serve the purpose of showing two altitudes, such as the SCH floor and the WCH ceiling. In this simulation, some pilots would have preferred flying inside a corridor rather than along a surface. Figure 6.1 shows one format for displaying two altitudes along with the terrain.

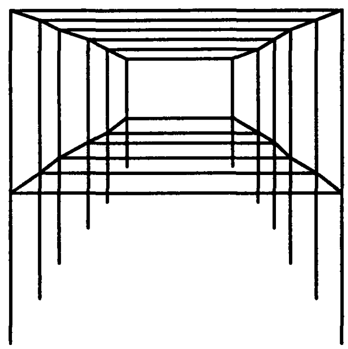


Figure 6.1: Tunnel Display Possibility

The base of the legs still would represent the terrain, but in this case a ceiling would show the pilot the maximum desired altitude. The height of the tunnel could change based on ground threats and terrain masking available in the area. A tunnel display would be most useful for commanding optimal turning recoveries based on PGCAS evaluation of ground threats, aircraft performance available, and terrain characteristics.

All of the displays could be improved by incorporating more information than just the minimum predicted clearance. Also, a smoothing filter would make the symbology more docile and predictable, eliminating most of the annoying jumps noted by the pilots.

6.2.2 Implementation

General guidelines regarding implementation of advanced PGCAS displays arise from this project. First, using pilot acknowledgement allows more informative symbology, which remains on the HUD until the pilot chooses to remove it. A more demanding system would require the pilot to physically move a switch or push a button; an alternative system might assume acknowledgement once the aircraft has maintained a safe altitude for a set period of time.

Displays should not clutter the HUD, nor test the drawing capabilities of the image generator. A built-in safety factor is a necessity, so it is desirable to show a clearance height that still allows for some error without catastrophe.

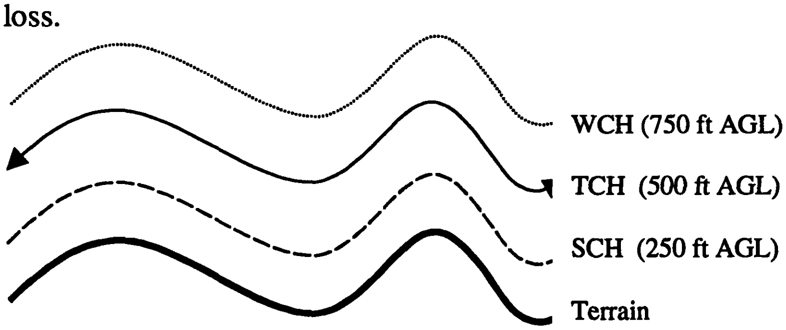
The pilots in this experiment preferred a roll stabilized, dynamic display that provided preview information. Granted, the limited-visibility TF/TA task examined here is only one situation when a PGCAS alert might occur. Still, further research would likely prove continuous displays viable for visual recoveries any time accurate flightpath control is desired. Implementation of advanced displays such as these would save tax dollars and, more importantly, the lives of pilots who risk CFIT each time they fly.

Appendix A - Pilot Instructions

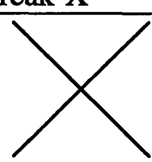
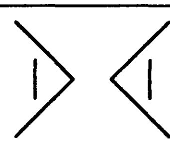
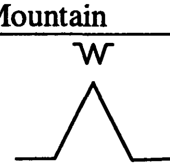
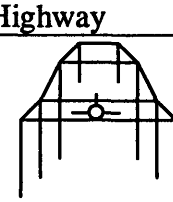
This experiment will test your ability to recover a T-38 aircraft in the face of impending ground collision. The Head-Up Display is your primary source of flight information. You should leave the throttle at military power for the duration of the experiment, and do not use the trim switch or flaps.

Your task will be to follow a series of flight director cues under instrument meteorological conditions. These cues will simulate air traffic control directives or terrain following commands you might receive. You should pitch the aircraft to put your velocity vector on the black command symbol. You should then match your bank angle with that shown by the command symbol. You will not be scored on how long it takes to reach the command, so take sufficient time to do it carefully without large oscillations.

At some point in the flight, you will receive one of four possible ground collision alerts. The alert will occur when your projected trajectory crosses the Warning Clearance Height (WCH). You should not penetrate the Safety Clearance Height (SCH). Upon receiving an alert, you will use the standard military recovery: *first* rolling to wings-level, and *then* pulling up. Recover to the Target Clearance Height (TCH), and attempt to *maintain* this separation until the simulation is paused. The idea here is to avoid detection by ground radar and to prevent excessive energy loss.



The following table summarizes the four alerts you will encounter.

Name:	Break-X	Chevrons	Mountain	Highway
Diagram:				
Aircraft at WCH:	Not present	First appears	First appears	First appears
Aircraft at TCH:	*First appears*	*Touching bars*	*Touching A/C reference W*	*FP Marker level with surface*
Aircraft at SCH:	Present	Form X	Touches top of HUD	FP Marker well below surface
Aircraft at Terrain:	Present	Form X	Spreads to touch edges of HUD	FP Marker at bottom of posts

Appendix B - Informed Consent

Experimental Study of Head-Up Display Symbology
For Aircraft Ground Collision Avoidance

Research Assistant:
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Room 6228
C. S. Draper Laboratory
Cambridge, MA 02139

Principal Investigator:
Prof. James Kuchar
MIT Rm. 33-117
77 Massachusetts Ave.
Cambridge, MA 02139

Participation in this study is voluntary and you may stop or delay the experiment at any time. You may also withdraw from the study for any reason, without prejudice. If you have any questions concerning the purpose, procedures, or risks associated with this experiment, please ask them.

This study is designed to evaluate several candidate alerting displays for terrain avoidance during low-level maneuvering. You will be flying a T-38 flight simulator and looking at a screen that shows the view from the cockpit. During these flights, your task is to respond to terrain alerts by recovering the aircraft. An interview following the experiment may be audio taped to aid in recording comments. The tapes will contain no identifying information, and the experimenter will store them securely after the experiment. They will be destroyed within one year once conclusions have been drawn from the data. The study is expected to take a total of 2 hours to complete.

As with any flight simulation, you may or may not experience "simulator sickness," including disorientation, vertigo, dizziness, headache, eyestrain, fatigue, nausea, and in extreme cases, vomiting. You will continually be in voice contact with the experimenter, who will be stationed next to the simulator cockpit, and frequent rest periods will be provided. Please inform the experimenter at the first sign of any uncomfortable symptoms, and the experiment will be interrupted and an attempt made to alleviate the cause of the symptoms.

All data will collected in a confidential manner and will not be linked in any way to your identity. You will remain anonymous in any report that describes this work.

CONSENT

In the unlikely event of physical injury resulting from participation in this research, I understand that medical treatment will be available from the M.I.T. Medical Department, including first aid, emergency treatment and follow-up care as needed, and that my insurance carrier may be billed for the cost of such treatment. However, no compensation can be provided for medical care apart from the foregoing. I further understand that making such medical treatment available, or providing it, does not imply that such injury is the Investigator's fault. I also understand that by my participation in this study I am not waiving any of my legal rights.

I understand that I may also contact the Chairman of the Committee on the Use of Humans as Experimental Subjects, M.I.T. 253-6787, if I feel I have been treated unfairly as a subject.

I volunteer to participate in this experiment which is to involve flight simulation. I understand that I may discontinue my participation at any time. I have been informed as to the nature of this experiment and the risks involved, and agree to participate in the experiment.

____________________________ ____________________________

Date Signature

* Further information may be obtained by calling the Institute's Insurance and Legal Affairs Office at 253-2822

Appendix C - Pilot Questionnaire

Participation in this study is voluntary. You are free to decline to answer any question(s) or withdraw from the study at any time, without prejudice. Whether or not you complete the experiment, your confidentiality and anonymity are assured.

Personal Data:

Age:

Gender: M / F

Please list your pilot experience:

Total Hours:

Ratings:

Primary A/C:

Jet Experience:

Military Flight Experience:

HUD Experience:

Ground Collision Avoidance System (GCAS) Experience:

What strategies did you develop for following the alerts? Which do you think worked the best?

Did you encounter differences in your tendency to roll to wings-level before pulling?

Which alert did you prefer and why?

Do you have comments on the overall simulation? Fatigue? Rest time? Enough practice?

Which alert better helped you to avoid penetrating the lower Safety Clearance Height during the initial recovery?

Break-X — **Chevrons**

absolutely better	much better	better	slightly better	same	slightly better	better	much better	absolutely better

Break-X — **Mountain**

absolutely better	much better	better	slightly better	same	slightly better	better	much better	absolutely better

Break-X — **Highway**

absolutely better	much better	better	slightly better	same	slightly better	better	much better	absolutely better

Chevrons — **Mountain**

absolutely better	much better	better	slightly better	same	slightly better	better	much better	absolutely better

Chevrons — **Highway**

absolutely better	much better	better	slightly better	same	slightly better	better	much better	absolutely better

Mountain — **Highway**

absolutely better	much better	better	slightly better	same	slightly better	better	much better	absolutely better

Which alert better helped you to maintain the Target Clearance Height after the initial recovery?

Break-X — **Chevrons**

absolutely better	much better	better	slightly better	same	slightly better	better	much better	absolutely better

Break-X — **Mountain**

absolutely better	much better	better	slightly better	same	slightly better	better	much better	absolutely better

Break-X — **Highway**

absolutely better	much better	better	slightly better	same	slightly better	better	much better	absolutely better

Chevrons — **Mountain**

absolutely better	much better	better	slightly better	same	slightly better	better	much better	absolutely better

Chevrons — **Highway**

absolutely better	much better	better	slightly better	same	slightly better	better	much better	absolutely better

Mountain — **Highway**

absolutely better	much better	better	slightly better	same	slightly better	better	much better	absolutely better

Overall, which alert did you prefer?

Break-X								**Chevrons**
absolutely better	much better	better	slightly better	same	slightly better	better	much better	absolutely better

Break-X								**Mountain**
absolutely better	much better	better	slightly better	same	slightly better	better	much better	absolutely better

Break-X								**Highway**
absolutely better	much better	better	slightly better	same	slightly better	better	much better	absolutely better

Chevrons								**Mountain**
absolutely better	much better	better	slightly better	same	slightly better	better	much better	absolutely better

Chevrons								**Highway**
absolutely better	much better	better	slightly better	same	slightly better	better	much better	absolutely better

Mountain								**Highway**
absolutely better	much better	better	slightly better	same	slightly better	better	much better	absolutely better

Appendix D - Pilot Comments

What strategies did you develop for following the alerts? Which do you think worked the best?

1) **Break-X**: not very helpful.
2) **Break-X**: Oscillated a lot, pull hard then descend slowly using 10°-15° degree increments. **Chevrons**: aggravating, motion is perpendicular to reality, paid more attention to pitch ladder. **Mountain**: covered pitch ladder, so used it less. **Highway**: can use it inverted, put FPM on top of next hill, not valleys (would tend high)
3) **Break-X**: Put FPM just below horizon, wait for X. Can't be too effective for TF, but TA is good. **Chevrons**: pulling vertical but markers are horizontal. Looked only at half of it - no need for both. Pull or push? Tracking roll and flight path simultaneously is hard. **Mountain**: No info on what's ahead, coming. Lost track of bank, little hard to use W vs. FPM. Tried to think ahead of it, predict what it would do. **Highway**: hard to follow when terrain changes rapidly, which line am I at? Think of it as ground, oscillates with large terrain changes. Could disappear...where is it? Dotted on bottom?
4) **Break-X**: Noted altitude where alert happens, fly it more conservatively. Let down gradually, -10° FPA. Roll, then pull. More aggressive inputs, more confidence since had it last. **Chevrons**: info outside field of view, started scanning, then could take them in peripherally. Not much displacement between them - move vertical bars by scaling. Horizontal - less intuitive than vertical, only used one chevron. **Mountain**: show something when it goes off bottom of HUD. Make it roll. Fly it as a rate cue, not displacement. Went to -10° FPA, wait for it to come up, otherwise comes too fast. Exponential scaling also nice here. **Highway**: anticipation helps, exponential scaling would be nice to keep it from disappearing. Interpret as projected. Nice to change post spacing with terrain ruggedness. Try to fly the farthest trend...natural, easy to learn. Nearest bar moves quickly, whipping.
5) **Break-X**: not very good. Real life: go very positive till it disappears, then negative. Oscillatory, wastes energy and effort, not much feedback. **Chevrons**: Liked how speed of chevrons showed rate of terrain closure. Nor foreknowledge; peak produced large movement. Instinct is to just pull. **Mountain**: bad since referenced to W, not FPM. Tried to line up all three, use FPM as predictor for location of W. **Highway**: match up lines, collapse them if terrain is flat. Anticipate valley, peak, cut off top and bottom. Could interfere with tapes.
6) **Break-X**: held constant negative FPA until it reappears. Have to pull until it disappears. For alert, not for TF/TA, impossible to complete mission. Full back initially, float down to about -20° FPA. Not comfortable at all. **Chevrons**: Need more time between appearing and SCH, moved more slowly than Mountain. **Mountain**: between Highway and Break-X, could be useful in mild rolling terrain, not great for rugged terrain. Quick movement from bottom to top, no future projection. **Highway**: limited by number of lines HUD can draw. Can tell what terrain ahead is doing. Recovery inconsistent - typically, just enough to recover; makes pilot push -g often.
7) **Break-X**: rolled to 90, let nose drop through. Can push over, no indication of negative g. Note altitude when it appears. Uneasy feeling pulling down in IMC. **Chevrons**: Highway better, guidance but not command. Here, no information, just command. Not predictive, no planning. -10° FPA works fine for rate of indications. Don't like pushing over in IMC GCAS situation. **Mountain**: shape implies terrain shape, not necessarily true, distracting. No anticipation of when it will go down and away, easier to maintain steady state once I got it.

Highway: feels safe just under surface, too comfortable. Should feel worse underneath Highway surface. Hard to get right on. Airspeed and altitude dropped out of cross-check. Operationally, thin out bars.

8) **Break-X**: don't know what's ahead, mountain or flat. Overcorrect, err to high side. -5° or -10° FPA to get X to reappear. **Chevrons**: can't focus on HUD still. Horizontal doesn't match with vertical, moved slower than Mountain (worse), it seemed. **Mountain**: tendency to chase, can't really anticipate it. Could drop off screen, can't follow it exactly. Focus on it vs. chevrons. **Highway**: much better, can tell how far above should be. Anticipate much better, could use one full time for TF.
9) **Break-X**: impossible to track terrain, no preliminary warning. -20° increments on ladder to make X reappear. **Chevrons**: fine for initial pullup. If terrain moves, very difficult. 400-500 kts too fast for 500 ft clearance unless rolling terrain. Ambiguous if inverted, symmetric vertically. **Mountain**: fools you to think you're wings level, easier to use than Chevrons. Terrain unrealistic for this airspeed, though. **Highway**: best feedback, good roll info. Tend to damp out bumps, more info when slightly below Highway surface.
10) **Break-X**: got attention more than other two. No good, have to pull hard since don't know, pull until way high, then push negative g's. Go to -20° FPA, then up to wait at -5° or -10°. **Chevrons**: counterintuitive, can't imagine a mountain, but can use peripheral vision more. No info between 250 and 0 ft. **Mountain**: good because you could see rate. Tried not to go below -15° FPA. Tried to keep it on screen, get fixated on symbol. **Highway**: very good for getting attention. Break-X better for saying bad, add it to Highway. Fly lower if terrain ahead falls off, start pitching ahead of time. Could lead terrain more.
11) **Break-X**: insulting, not intended for terrain tracking, pure alert, binary. Uncomfortable feeling. **Chevrons**: not intuitive, reference frames perpendicular. Training could help, but in times of duress may still reverse control. This happened and was not easy to correct. When chevrons are gone or together, you are left with no info, lost. **Mountain**: axes aligned, much better. Lose sight of it, left with no info. Purely reactionary, no anticipation. Flew to -20° FPA, waited for it. Felt like my gain was higher for this display. **Highway**: best performance, reference frames intuitive. No distance-rate cueing, inner loop control, so I knew what to do in next 10 seconds but not during next 1 second. Can anticipate some, but not enough.
12) **Break-X**: couldn't stand it. No place was ok - either emergency or too high. Counterintuitive, to be ok, must put self in danger. **Chevrons**: hard to track when they disappear. Not intuitive to pull up because axes were perpendicular. Quick movement meant pull, even if movement was outward instead of inward (reverse control). Meeting seemed very bad, worse than Mountain flattening, centered in middle of screen. **Mountain**: pretty good, felt like doing well. Bothers that symbol is always level. Concentrating on tracking, forgot about roll. **Highway**: feels less stressful, less workload. Like it a lot, very easy to slack off, cut off bottom of valleys. Felt like I was doing something versus being commanded around.

Did you encounter differences in your tendency to roll to wings-level before pulling?

1) -
2) Highway best for roll indicator
3) Highway very nice for rolling to wings-level, Chevrons and other two much more difficult. Would need to be a habit.

4) Mountain: Was used to other one rolling, didn't think about it till end. Rolling alert allows quick assimilation of data.
5) Highway was good for helping recover, gave roll information. Break-X not as good as Highway. Chevrons and Mountain could be rotated.
6) Experience helped with rolling first, all should be roll stabilized.
7) Break-X: Some loaded rolls, some unloaded. Instinct calls for loaded roll. Highway: pause between command and Highway appearing, still headed down because knew ground was coming. Chevrons: preferred over Mountain; more anticipation. Mountain: gives illusion of wings-level, vertical orientation.
8) Break-X: forgot once. Highway: more cues of wings-level. Mountain: false illusion that wings are level, translates to physical cue. Chevrons: Easier to remember to roll first, iconic.
9) Mountain: worse than Chevrons, false illusion of wings-level. Break-X: better for roll. Highway: best, very natural.
10) Chevrons, Mountain, Break-X about the same. Highway much better.
11) Chevrons, Mountain gave no intuitive cues for rolling, override world reference frame. Better to roll stabilize them. Highway: much better for rolling to wings-level, natural to view it in vertical, try to roll until it is vertical.
12) Mountain: Remembered to roll initially, forgot after that sometimes. Chevrons: about same as Mountain, both fixed. Highway: roll-stabilized, makes a big difference, more immersive. Looks like ground, not sure what it represents. Break-X: same as Chevrons, Mountain, but a little better because not concentrating on tracking.

Which alert did you prefer and why?

1) Either the Chevrons or Highway: using the Highway it was hard to keep the TCH. Using the Chevrons it was the easiest to keep the TCH. Tempted to fly inside the Highway, feel lost above it. Mountain pretty good also.
2) Highway: good roll indicator, shows info ahead, what is coming.
3) Highway: modifications would be useful. Predictive - sharp/dull pullups. Could "see" terrain.
4) Highway: fly it as trend, flight cue.
5) Highway: gives info ahead of time. Flat terrain: any but Break-X. Peaky terrain: hard to keep up with Chevrons, Mountain.
6) Highway: more SA, more information presented than current or set distance.
7) Highway, then Chevrons, then Mountain, then Break-X.
8) Highway, then Chevrons, then Mountain, then Break-X.
9) Highway best overall, Chevrons were counterintuitive, no roll information.
10) Highway, then Mountain, then Chevrons, then Break-X.
11) Highway, then Mountain, then Chevrons, then Break-X.
12) Highway, then Mountain, then Chevrons, then Break-X

Do you have comments on the overall simulation? Fatigue? Rest time? Enough practice?

1) OK
2) Sometimes knew when alert was coming. Some fatigue near end, possibly learning
3) Possibly small improvement through simulation, sitting in sim is best training.
4) Fly to vs. fly from on command symbol, confusing. Time to Impact vs. Altitude to Impact. Mountain - noise at about 1 ½ Hz.

5) Didn't feel like same terrain for all four, couldn't remember when alert was coming, probably improved through runs, not through alerts.
6) Plenty of practice. Break-X is hardest, Highway easiest. No improvement through runs.
7) Highway: great knowing terrain ahead, show ground, SCH, maximum desired altitude.
8) Learning through alerts, also through runs. Could tell by memory that mountain is coming.
9) Abnormal task to use sign of impending danger to track, confusion between X and tracking. Would want Highway poles to move past, show 10-20 seconds ahead. Make it uncomfortable to crash, warn more against it.
10) Trimmed once. Sim was realistic, appeared random. Learning through runs. Plenty of practice, some learning about dynamics.
11) Much more confident with Mountain than Chevrons, could be learning. First 3-4 runs, still getting used to dynamics. No fatigue, boredom, timespan ok.
12) Terrain pretty crazy. First rung of Highway unattached. Could put it in bold, change Highway to different color when underneath surface. Cluttered display.

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