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# F-16 MMC Strafe in Mountainous Terrain

by

Jared P. White, Maj, USAF



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Advisor: Dr. Dennis Duffin

Maxwell Air Force Base, Alabama

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## Abstract

High-angle strafe is the preferred strafe procedure in the F-16 community. Current tactics do not adequately address the execution of this procedure in mountainous terrain. Current area of operations is extremely mountainous and CWDS does not model complete recovery ground clearance in the event of strafe into rising terrain. Research into approved techniques and analysis of those techniques in mountainous terrain was conducted to determine if safety margins are preserved. In most circumstances, high-angle strafe provides adequate terrain clearance.

In circumstances where execution is at the limit of dive angle and airspeed, terrain clearance safety buffers were violated. Due to programming logic to minimize nuisance recoveries, AGCAS cannot be relied on to maintain ground collision avoidance. When attacking into rising terrain, analysis recommends a hybrid strafe attack. This attack uses low-angle strafe dive angles and high-angle strafe attack ranges. Fuze function, normal sight picture, and required terrain clearance is maintained by utilizing this technique.

Research also resulted in four additional recommendations. First, AFI must clarify VFR and combat terrain clearance operation in mountainous terrain and define mountainous areas by AOR. Second, WSEP must analyze the percentage of acceptable 20mm fuze function based on impact angle and velocity at the edge of the design specification envelope. Third, the 16 WPS must evaluate the tactics suggested by this analysis and disseminate to the CAF if desired. Fourth, incorporate maximum gun range symbology based on fuze function and minimum range symbology based on planned recovery procedure and pilot entered minimum recovery altitude in future OFPs.

# Introduction

Due to a high-profile accident that occurred in 2007, the F-16 community has dramatically altered the tactics, technique and procedures (TTPs) utilized during strafe. Specifically, due to safety concerns over ground collision, the community has transitioned to primarily executing high-angle strafe that procedurally has the pilot executing at relatively extended ranges and recovering 1000 feet height above target (HAT). Additionally, operational flight program (OFP) updates have changed some of the assumptions upon which these TTPs are based. Furthermore, while several research papers have been written on the subject of strafe TTPs across multiple aircraft mission design series (MDS), they all assume execution over level terrain. Current area of operations (AORs) call for strafe in rugged mountainous terrain. In this environment, is high-angle strafe or low-angle strafe preferred in mountainous terrain? (Fig. 1)



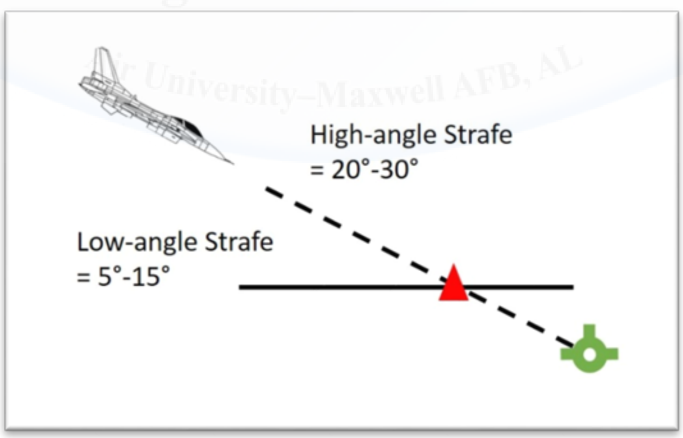


*Figure 1. Low and high-angle strafe (relationships not to scale)*

Modular mission computer (MMC) 6.2 OFP introduced auto-ground collision avoidance software into the digital flight control computer (DFLCC). AGCAS provides an additional safety buffer by automatically initiating an aircraft recovery if current flight parameters put the aircraft in a position where it is at risk of ground collision. Rising and falling terrain can influence this modeling and have a negative impact on the ability to execute the desired tactic.

Additional updates to F-16 software have attempted to overcome some of the issues associated with high-angle strafe. Because of the increase employment ranges and altitude, target tracking and identification is more difficult when employing high-angle strafe versus low-angle strafe. Laser spot search and track, target identification system, laser (TISL) and an improved strafe reticle are some examples of updates designed to improve chances of successful execution. However, because the weight of effort has been put towards improving high-angle strafe, little effort has been spent on re-addressing the merits of low-angle strafe. Therefore, analysis will address whether low-angle or high-angle strafe is the preferred tactic in an AGCAS equipped F-16 when employing in mountainous terrain.

To address this subject, the two employment methods have been evaluated against the rate of successful employment both within normal safety margins and varying terrain types, weapon fuze function and ease of target identification by analyzing the geometry of the two attack options against various degrees of rising terrain.



## Background

On 27 November 2007, Major Troy Gilbert responded to a “troops in contact” (TIC) situation approximately 20 nautical miles northwest of Baghdad.[1] An Air Force press release published on AFNet summarized the results of the accident investigation board as an extremely difficult scenario involved enemy troops in close proximity to friendly forces. In this instance, enemy forces were firing on friendlies with truck-mounted heavy machine guns, mortars, and small arms.[2] Because of the proximity of the enemy to the friendly troops and the need for immediate effects on the target, Major Gilbert executed strafe. After his first successful engagement, Major Gilbert set up for an immediate re-attack that was ultimately too low for recovery.[3] Major Gilbert impacted the ground during his second run and was killed on impact.[4]

The accident investigation board (AIB) concluded that “channelized attention manifested by his desire to maintain a constant visual positive identification of targeted enemy vehicles and subsequent target fixation on these vehicles while they were traveling at a high rate of speed” and sparked an effort to standardize strafe execution to minimize this safety risk.[5] The result was a transition from technique based execution based on preferred individual sight pictures, execution ranges, etc. to a more procedural based high-angle strafe tactic. Air Combat Command (ACC) would go on to publish flight crew information file (FCIF) that directed the use of this newly developed strafe tactic. (Need to dig up this FCIF which directed airspeed, base altitudes, employment ranges, and recovery altitude).

Although low-angle strafe was still considered a valid employment procedure, the seemingly directive nature of guidance from ACC made high-angle strafe the de facto procedure. The procedure ultimately evolved over the course of the next year or so by increasing recovery altitude from 500 ft to 1000 ft, providing multiple procedures for base/entry altitudes and time on final and directing different communication requirements amongst aircrew prior to employment. This tactic also highlighted some shortcomings inherent to the then current F-16 OFP.

Future F-16 OFPs would incorporate updates that would attempt to correct many of these shortcomings. An improved air-to-ground strafe reticle was one of the first OFP changes. This improved reticle was larger and made target identification easier as well as provided visual ranging information within the reticle itself (prior reticles required the pilot to take his eyes off the target and process raw range data). The Sniper Advanced Targeting Pod would incorporate new laser spot search functionality that would allow a dedicated fighter to lase a target while the strafing fighter could quickly match his sensor to aid in target tracking and identification. Finally, a TISL display in the heads-up display (HUD) would display to the pilot exactly where the laser spot search and track was located allowing the pilot to simply align the reticle to the TISL. These updates, for the most part, alleviated issues that arose from the newer high-angle strafe procedures and increased employment ranges.

June 28th, 2011, Capt Eric "Dirk" Ziegler was flying high aspect basic fighter maneuvers when he experienced G-induced loss of consciousness (G-LOC). Dirk was killed when his F-16 impacted the ground in the Nevada Test and Training Range (NTTR). Dirk, a member of the 422 Test and Evaluation Squadron, was accomplishing a weapons instructor course (WIC) spin-up ride. The loss of this extremely talented F-16 pilot, husband, and new father shocked both the entire Viper community and the fighter test world. The loss of Dirk was a catalyst to finally fund and field AGCAS.



This system functions by cross-referencing current flight parameters against a digital terrain elevation data (DTED) map. Air Force Technical Order 1F-16CM-34-1-1 describes AGCAS operation as"when a collision is predicted, the DFLCC will take control of the aircraft and perform an aggressive automatic recovery consisting of an abrupt roll to wings level at up to 180 degrees per second roll rate in CAT I (up to 150 degrees per second in CAT III) followed by a nominal 5g pull to clear the threatening terrain."[6] The initiation of this recovery occurs 1.5 seconds prior to the aircraft arriving at the computed point that ground impact cannot be avoided.[7] The AGCAS system is designed to provide nuisance free operation on missions down to 500 feet AGL, but an additional setting can be utilized for missions that require lower altitude operation or operation in mountainous terrain.[8] These modes provide a lower buffer and, therefore, a lower level of protection against ground collision. Finally, an AGCAS STRAFE mode is automatically activated when the pilot selects the gun for employment in the air-to-ground master mode.[9] The AGCAS STRAFE mode provides the smallest buffer for terrain avoidance.

The AGCAS scan pattern is "intended to cover all terrain that an AGCAS recovery could possibly pass over if initiated from current conditions".[10] For this reason, and considering this system is fairly unobtrusive, there are some scenarios where the AGCAS could initiate a fly up when it is unwarranted. These scenarios are generally when flying at extreme dive angles and mountainous or rising terrain. This exact scenario is one that a pilot could expect to experience when strafing in the current area of responsibility (AOR).

Finally, AGCAS does not disable the gun system in the event of a recovery. Testing discovered that the AGCAS system would initiate recovery just short of the low-angle strafe foul line located at 2000 feet range to target.[11] In the event a recovery is initiated during strafe attacks, the pilot must immediately terminate firing or risk hitting friendly personnel long of the intended target.



## Established Research

Several unclassified research papers have been written and published addressing various options for executing both high and low-angle strafe. These papers span across multiple MDS's and target types. However, none of these papers address strafe concerns associate with mountainous terrain nor have any been written since the fielding of AGCAS. AGCAS offers a new layer of safety against the risk of controlled flight into terrain (CFIT) and must be reanalyzed in this type of environment.

“F-16 Strafe Tactics for CAS” by David Epperson is the most current tactics paper written on the subject of F-16 strafe. While somewhat dated, it was published in 2005, Epperson primarily addresses TTPs associated with low-angle strafe. Epperson did not address any considerations for employing with AGCAS or in mountainous terrain, but, since it was written prior to those previously mentioned high-profile accidents and the Viper community transitioning to high-angle strafe, the techniques recommended were utilized in analysis for considerations in this research.

Two years following David Epperson’s paper, Major Ricardo Colon published “Employing the M61A1 Against Moving Vehicles”. Ricardo Colon further evaluated options for employing the F-16’s gun system. The techniques presented primarily address gun reticle placement and lead in reference to moving vehicles, speed estimation and strafe wire correction (based on head angle attacks resulting in steeper than planned dive angles and tail angle attacks resulting in shallower than planned dive angles).

In 2010, Kenneth Juhl published a tactics paper titled, “Optimizing 20mm Strafe in F-15E”. Capt Juhl’s paper was written as a result of a Strike Eagle class A mishap that resulted in the loss of the crew. The accident board pointed towards the lack of standardized communication and execution as a factor in that incident resulting in an effort for the Strike Eagle community to standards strafe tactics (similar to the realization the Viper community had previously established). Capt Juhl concludes with a recommended standard strafe attack that mirrors many of the assumptions used in F-16 strafe.

No other research papers have been published on this specific subject, however, the Air Force Tactics Techniques and Procedures 3-3.F-16 series of publications continues to update strafe tactics. The most recent version of this publication was signed in 2014. The 3-3 does not provide any guidance or techniques for executing strafe in varying terrain, but rather focuses on strafe TTPs to use in the "vacuum" of a controlled air-to-ground range.

## Attack Requirements and Criteria

There are several factors to consider when not only making the decision to execute strafe, but also when choosing which method of strafe to execute. First, what are the target types and desired effect? What are the entry and recovery parameters and terrain in relation to planned attack geometry? How to maintain target track and identification throughout the entire attack?

The first consideration is what is the target and is this weapon effective for that target type? The 20mm round is effective against a myriad of targets. However, it is generally selected due to the proximity of enemy forces to friendlies. The Joint FIRE TTP lists risk estimate distances (RED) for all air-to-ground munitions. These distances are based on a 1-in-1000 chance of friendly incapacitation from a weapons (known at .1% PI). The .1% PI RED number for a 500-pound class general-purpose weapon is 310 meters for example. The same class of weapon with a laser guidance system has a RED number of 280 meters. Strafe .1% PI is much tighter at only 95 meters.[12] The RED number for 20mm is tighter because, "the 6-mil dispersion translates to 36 feet for high-angle strafe and 21 feet for low-angle strafe normal employment ranges".[13] This gives the ground commander options for fixed-wing employment when operating close to enemy forces. Because of the inherent difficulties in target ID and the increase likelihood of being a strafe target, personnel in the open is the only target type considered in the analysis for this paper.

The PGU-28 semi-armor piercing high explosion incendiary (SAPHEI) round is the most commonly used round across fighter aircraft equipped with the M61 gun system, including the F-16. This SAPHEI round contains a fuze that is armed by the rotational energy experienced by the rifling of the barrel when firing. The fuze then needs an impact velocity of approximately 1000 ft/sec impact force to function.[14] Below 1000 ft/sec, the round has limited effectiveness against troops in open. Firing greater than 7000 feet from the target results in impact velocities below 1000 ft/sec.[15] Another round, the M-56 series ammunition, still in limited use, requires the same impact velocity but is hampered by a less efficient aerodynamic profile.

## Mountainous Terrain

The Oxford English Dictionary defines a mountain as "a natural elevation of the earth surface rising more or less abruptly from the surrounding level and attaining an altitude which, relatively to the adjacent elevation, is impressive or notable".[16] The FAA, without a set definition, is responsible for designating mountainous terrain in the continental United States (CONUS). Operating in "mountainous" terrain requires the pilot to execute different IFR terrain clearance. Air Force Instruction 11-202 volume 3 defines mountainous terrain as "a 500 ft surface elevation change over a ½ NM distance".[17] Again, pilots operating under IFR are required to maintain additional terrain clearance. Air Force pilots employing in combat scenarios are not necessarily required to maintain these higher terrain clearances, but the general practice should be considered. In that regard, any Air Force instruction directive or TTP designed for practice in level terrain should be padded with an additional safety margin when operating in mountainous terrain. At the very least, pilots should not press any closer than safety buffers established for level terrain.

## Target ID

The F-16 will generally operate at medium altitudes of 15000 to 20000 feet. Because these altitudes make target ID difficult, aircraft OFP updates and targeting pod updates have greatly aided the Viper pilot's ability to maintain positive target identification. Most of these updates assume a minimum force of two F-16s. While this is a true assumption when considering scheduling of assets, aerial refueling or a requirement to have both fighters attack simultaneously could result in a loss of mutual support for target ID.

In a normal scenario, a single fighter will generally hold high and maintain target ID and pass sensor data to the other fighter as he executes the attack. If this mutual support breaks down, the pilot workload increases in an attempt to maintain positive target ID. To cope, the pilot has a couple options. First, the pilot can utilize larger features to maintain positive ID. Buildings, military equipment and lines of communication are examples of these larger features that can utilized to aid in maintain situational awareness on target location. The other option is to decrease altitude. This allows smaller features (personnel for example) to become observable. Flight at lower altitudes results in altered employment options. High-angle strafe requires a minimum of 8000 feet AGL while low-angle strafe can be entered from the lower altitude of 3000-5000 feet AGL.

While improving observable cues from the "MK-1 eyeball", Descending to the low-altitude structure introduces additional concerns for a fast single-seat close air support (CAS) fighter. First, the pilot is required to time-share ground avoidance in addition to other tasks. This increased workload reduces the time available for target tracking, sensor operation, and CAS procedures. Second, structural and environmental obscurations have a greater influence on sensor coverage. Lower graze angles can exacerbate any vertical build-up and provide the target more coverage than from a fighter operating and higher altitudes.  Third, lower altitude operation exposes the fighter to additional threat envelopes (in this case, small-arms fire).  Given these trade-offs, there is no definitive advantage to one altitude structure over another.

**Attack Recovery and Safety Margin**

Current high-angle strafe TTP's establish certain entry, employment and recovery assumptions to facilitate overall safe employment.  These assumptions or primarily based on entry height above terrain/target (HAT), roll-in rate, G application, dive angle based on depression from the horizon, employment range, employment airspeed, recovery range and finally recovery G.  Additionally, it has been determined that 1000 feet AGL provides and appropriately safe recovery buffer.[18]  Therefore, an attack formulated on assumption of an 8000 foot AGL entry, roll rate of 90 degrees per second with 3 G pull, a 30 degreed max dive angle based on depression angle from the horizon, employment range of around 5000 feet, airspeed employment and recovery of approximately 400 knots indicated airspeed, a 5 G recovery executed within 2 seconds and remaining above 1000 feet regardless of any consideration for extreme changes in terrain elevation may, despite the operators best attempt to execute within those criteria, be flawed.[19]



The assumption utilized to build low-angle strafe TTPs are the same as high-angle strafe in regards to roll-in, airspeed, burst length and recovery G, but differ in depression angle (10-15 degrees below the horizon) and an employment range of 3500 feet, but no closer than 2000 feet.[20]  Again, this attack geometry is changes when employing against rising terrain.

Take, for example, a hypothetical strafe scenario in Shahi Kot Valley in the Eastern portion of Afghanistan (the 2002 site of Operation Anaconda the first large-scale offensive in

Afghanistan). Shahi Kot Valley sits at an elevation of approximately 7500’, and is surrounded by mountains that rise up to 12000’. The foothills of these mountains rise approximately 2300’ in a mile and a half. While not perfectly uniform, the average angle of rise is almost 13 degrees. During Operation Anaconda, one of the objectives was to attack insurgents embedded in these foothills (as well as insurgents further up the terrain). Additionally, blue forces ran parallel to rising terrain along the length of the valley. Because of the blue order of battle, standard strafe tactics (had strafe been required for this operation) would call for fighters attacking perpendicular to the line of blue forces, also known as “over-the-shoulder”. This attack geometry would put the fighter pointing directly at the rising terrain.

In this example, a normal high-angle strafe depression angle of 25-30 degrees would result in a higher than expected of 37.5 to 42.5 degrees (Fig. 2). Executing a normal cease-fire range of 5000’ and 5g recovery would result in the aircraft passing clear of the normal recovery buffer of 1000’. Based on a normal attack airspeed of 450 KTS and 5g recovery, the F-16 has a turn radius of approximately 3515 feet (Fig. 3). With 2-seconds assumed from cease fire to full 5g recovery established, the jet will travel an additional 1500 feet down track. Continuing through the recovery, the pilot will safely pass at 1000 feet over target elevation, and continuing the recovery, pass no closer to the rising terrain (Fig. 4). In the event of more steeply rising terrain, the Viper driver will find himself passing even closer to the ground.

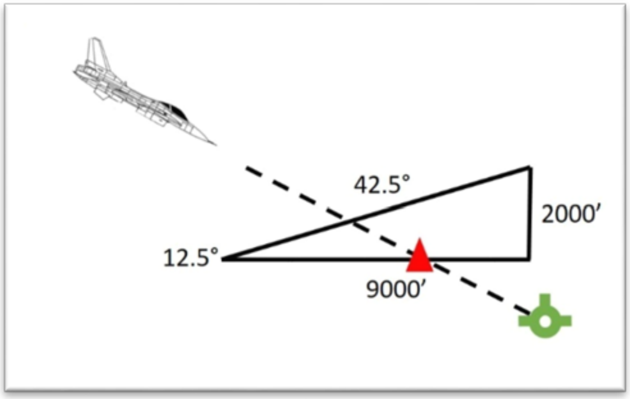


Figure 2. Shahi Kot Valley strafe perspective

$$Accel\ Force = \frac{V^2}{r}$$

$$\frac{450nm}{hr} x \frac{1hr}{60mins} x \frac{1min}{60sec} x \frac{6000\text{ft}}{1nm} = \frac{750ft}{sec}$$

$$1g = \frac{32ft}{sec^2}$$

$$5g = \frac{750\text{ft/sec}^2}{r}$$

$$r = \frac{562500}{160}$$

Figure 3. Fighter radius calculation

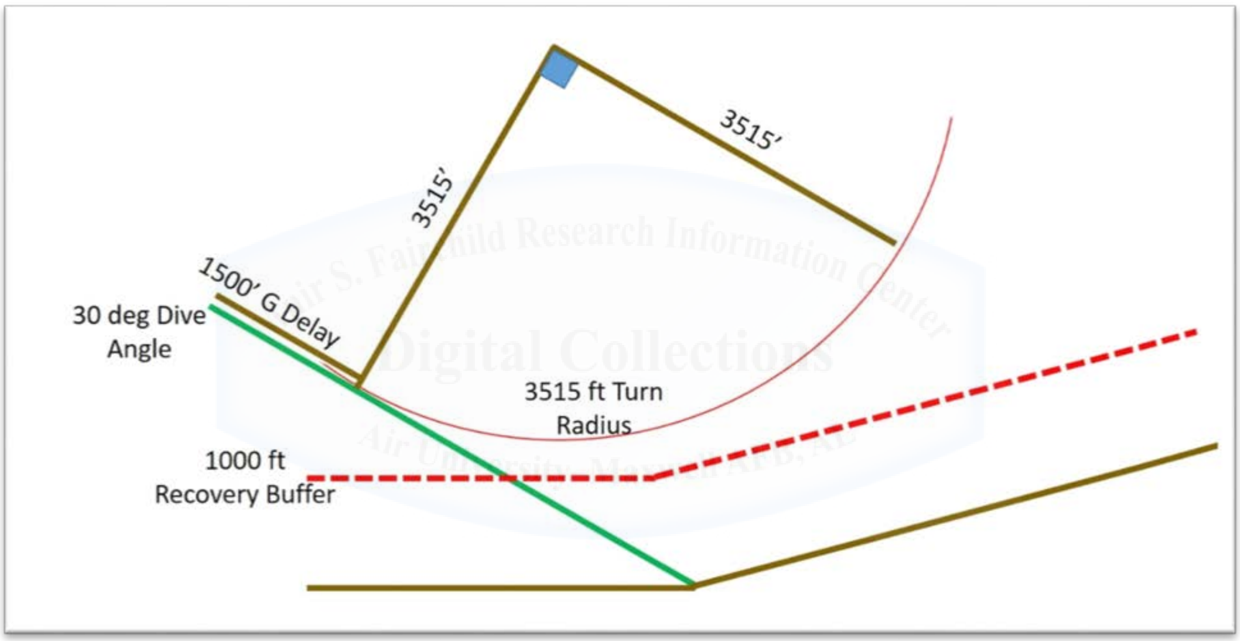



*Figure 4. High-Angle strafe recovery (relationships to scale)*
*These figures portray strafe attack geometry. The green line represents the dive angle of the fighter. The start of the green line depicts cease-fire range. The brown section above the line represents two second G onset delay as well as 90 degree geometric relationship for recovery turn radius. The solid red line represents the flight path for recovery based on recovery radius. The segmented red line is the directed recovery buffer. The bottom brown line represents terrain.*

Low-angle strafe executed at a 15-degree dive angle in the same scenario results in an actual angle coincident with the terrain of approximately 27 degrees. This puts the dive angle in the normal window for high-angle strafe. However, low-angle strafe employment ranges typically start at 3500 feet with a cease-fire of 2500 feet. With the planned 2-second delay, initial recovery occurs right at 75 feet, but with rising terrain, the aircraft will pass inside the minimum recovery buffer of 75 feet shortly thereafter (Fig. 5). Additionally, executing those tactics in rising terrain will put the aircraft in a position where there is a high risk of ground collision (or at least passing within the 25 foot buffer of AGCAS activation). Because this attack places the aircraft on an intercept with terrain, it would be expected that AGCAS fly-up would occur prior to, or during, the strafe attack.

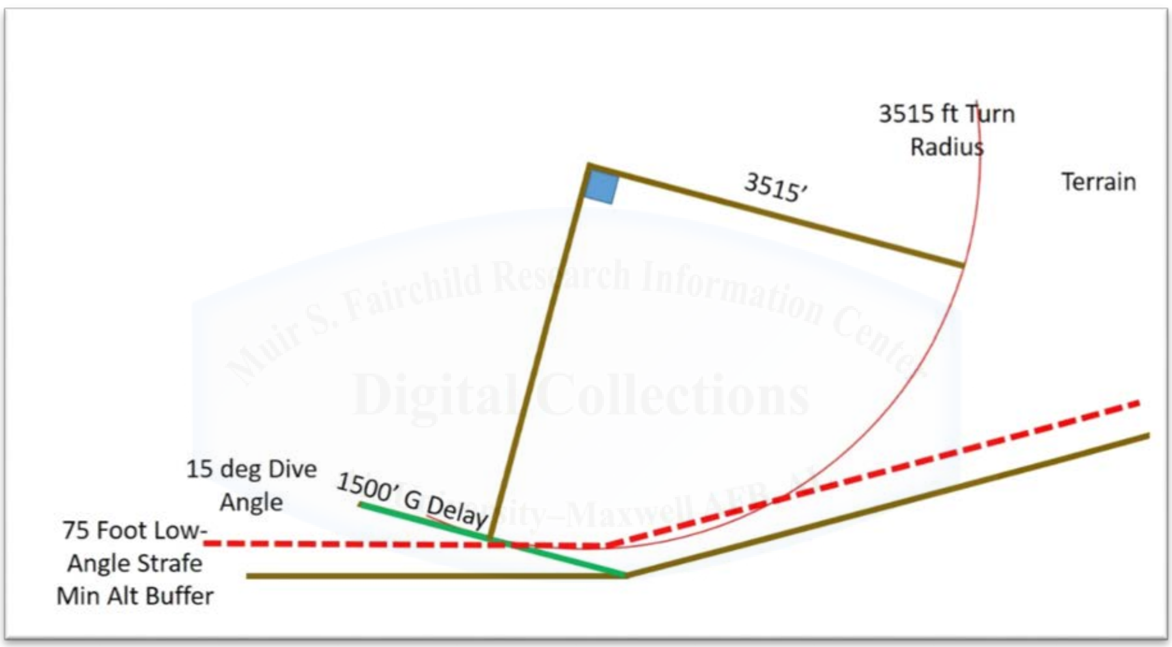


*Figure 5. Low-angle strafe recovery (relationships to scale)*

If identified, strafe dive angle exceeding 30 degrees should be abandoned.[21] However, this only applies to depression angle from the artificial horizon. There are no avionics displays in the F-16 that would warn the pilot that actual dive angle exceeds 30 degrees when attacking into rising terrain, and can only be recognized by experience and observing a sight picture that is steeper than expected. Aggressive roll-ins or high-to-low direct entry from 180 degrees out from the target may cause a fly-up due to expanding the AGCAS terrain scan pattern. Furthermore, an attack attempt into the mountains with more extreme rises, could trip AGCAS logic prior to normal attack ranges in the instance of low-angle strafe.

In the NORM operating mode, AGCAS provides a typical buffer of 154 feet of terrain clearance.[22] However, in strafe, that buffer is reduced to a typical clearance of only 9 feet with maximum buffer clearance of 25 ft.[23] This buffer only accounts for terrain and does not provide any additional clearance for man-made objects or trees.[24]

**Attack Analysis**

Having established a nominal scenario, it is only pertinent to explore other potential scenarios. Analysis demonstrated that executing the standard high-angle strafe tactic into moderately rising terrain of only 2 feet for every 9 across the ground (or 12.5 degrees of average terrain rise) would still maintain clearance above the commonly established terrain safety buffer of 1000 feet. Analysis also demonstrated that this moderately rising terrain was enough to either render low-angle strafe tactics un-executable (due to constant obtrusive AGCAS fly-ups) or, even more damning, unsafe and unrecoverable.

Mountainous terrain in the current AOR is greatly varied and includes rises up to sheer rock faces near 90 degrees straight up. It is highly unlikely that strafe would be called upon against the extremes of a 90-degree sheer cliff or that a target could establish itself on such a rock face, so, for the purpose of this analysis, it was disregarded. Based on research conducted in 1992 by Kinsella-Shaw et. al. on the perception of "walk-on-able" slopes, the human mind can perceive the maximum walkable incline of approximately 30 degrees.[25] Terrain does not rise in a uniform fashion, but rather at these inclines, is a mix of vertical spikes and horizontal steps. The speed associated with fighter strafe tactics has the effect of "smoothing" this terrain over distance. To someone wishing to climb these slopes, however, these jagged vertical rises and horizontal steps create a more “climbable” slope than a uniform incline. It is also assumed that a pilot executing strafe against terrain rising greater than 40 degrees would be presented with a near vertical sight picture and abort the attack. Therefore, the analysis only evaluated attacks against an average terrain rise of up to 40 degrees.

The Shahi Kot Valley example demonstrated the safety margins (or lack thereof) available for both high-angle strafe and low-angle strafe attacks against terrain rising at approximately 15 degrees. Running the same attack against terrain that rises at 1 foot for every 2 feet horizontal (or 30 degrees) results in the fighter pushing even closer to the terrain, but still well above the 1000 foot safety buffer (Fig. 6). It was noted that the altitude above the safety buffer is lower between the initial recovery and that above the rising terrain. A recovery that initially dusts off the 1000 foot buffer (do to delayed recovery or pressing an attack, for example) will pass considerably closer as the terrain rises (Fig. 6).

At 40 degrees of terrain rise, or slightly less than 1 foot of rise per foot of horizontal distance, the Viper driver will find himself passing right at the 1000 foot safety buffer. Furthermore, a pressed attack or delayed recovery that initially clears terrain by 1000 feet will ultimately press well within 500 feet during the recovery (Fig. 6).

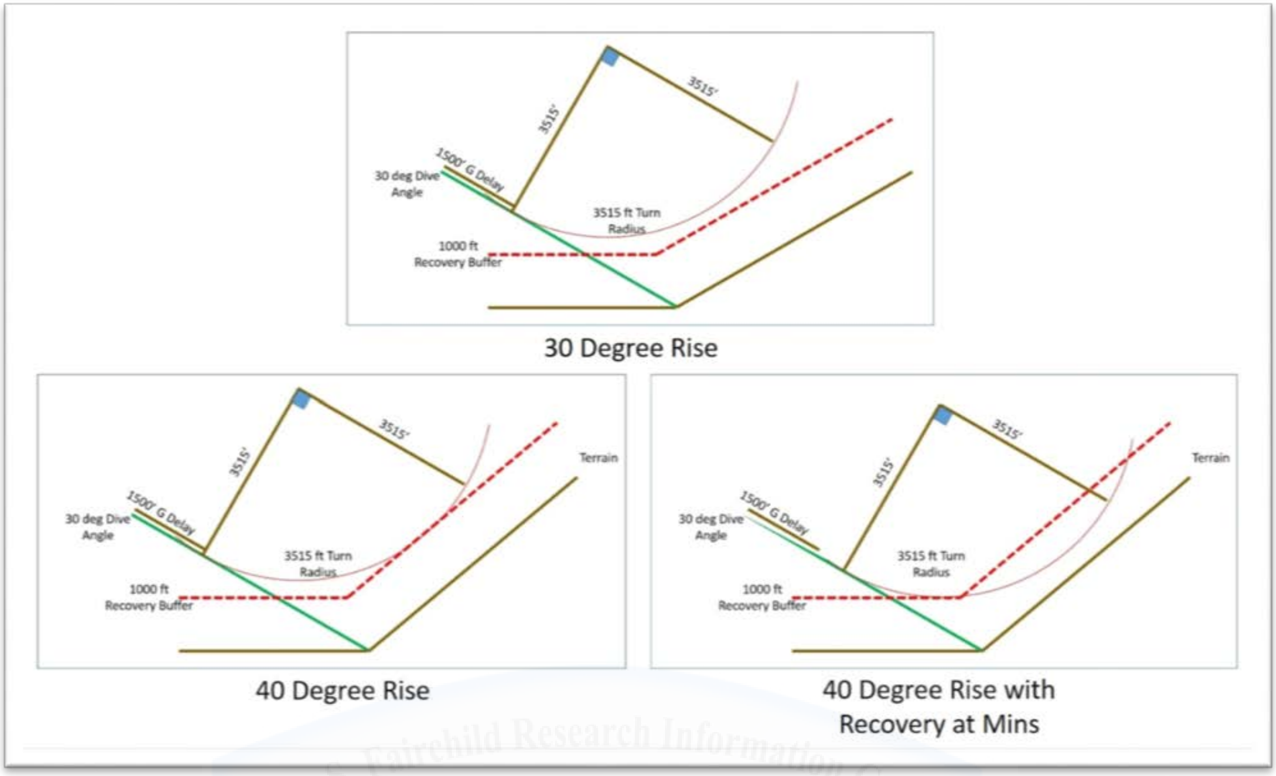


*Figure 6. High-Angle into steeply rising terrain*

The results are more dramatic for low-angle strafe. Terrain rises of 15 degrees already demonstrated the risk of passing below the minimum required safety buffer of 75 feet and potentially within 25 feet of the terrain itself (potentially initiating AGCAS fly-up prior to or during an attack). The 1 foot vertical in 2 foot horizontal terrain rise required for a 30 degree incline would result in a recovery that places the aircraft beyond the terrain impact point (Fig. 7). In other words, with only 5 G available, AGCAS would initiate recovery at, or during, normal low-angle strafe employment ranges. Without AGCAS input, the pilot would be in an unrecoverable situation (again, assuming only 5 G available).

If a pilot were to execute low-angle strafe into terrain rising at an average of 40 degrees, AGCAS would initiate fly-up prior to, or at, normal employment ranges (Fig. 7). Worse case, if the pilot experiences target fixation (a known condition when the pilot only focuses on the target and does not process other peripheral inputs) and AGCAS fails to initiate a fly-up, the aircraft would impact the terrain shortly after initiating recovery. There is no requirement to analyze min recovery efforts, as this attack places the aircraft beyond that scenario.

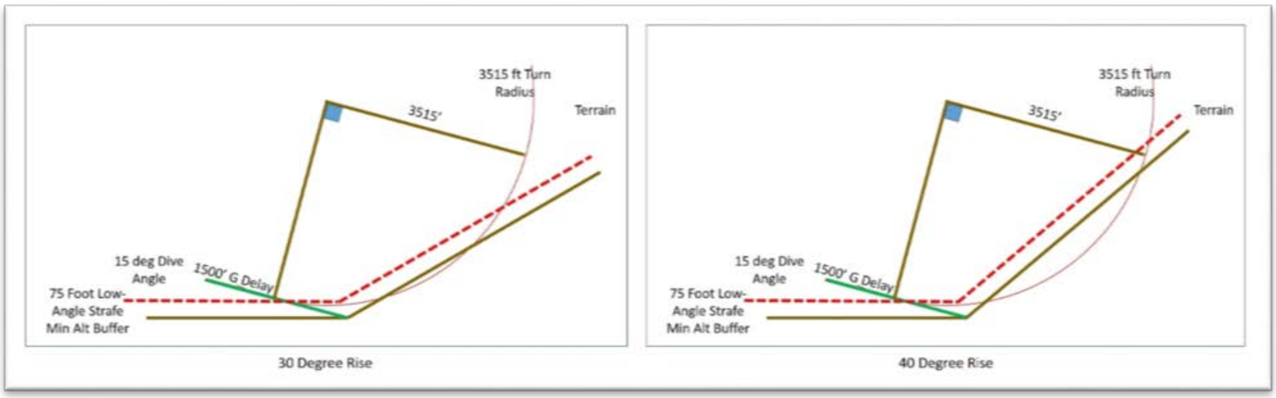


*Figure 7. Low-Angle into steeply rising terrain*

This analysis has demonstrated the perfectly executed standard high-angle strafe procedures for dive angle, speed and recovery G allows for safe execution at or above steeply rising terrain. This analysis also shows that using these same assumptions, a pilot will clear level terrain well above the planned recovery altitude of 1000 feet AGL. So, why the additional safety requirements? It is fairly uncommon to execute an attack on exact parameters. For that reason, diving attacks are planned within a window of parameters. For example, a single attack planning generally includes runs that are on parameters, steep on speed (previously addressed), shallow on speed, shallow and fast and, finally, steep and fast.

Examining an on-speed but shallow (20 degrees) high-angle strafe attack shows the 1000 foot safety buffer is preserved. In fact, due to the decrease depression angle but equal execution range, the attack brings the pilot close to the minimum recovery altitude at recovery initiation, but well clear throughout the remainder of the recovery. Regardless, all on-speed shallow high-angle strafe attacks into rising terrain maintain the minimum required safety buffer (Fig. 8).

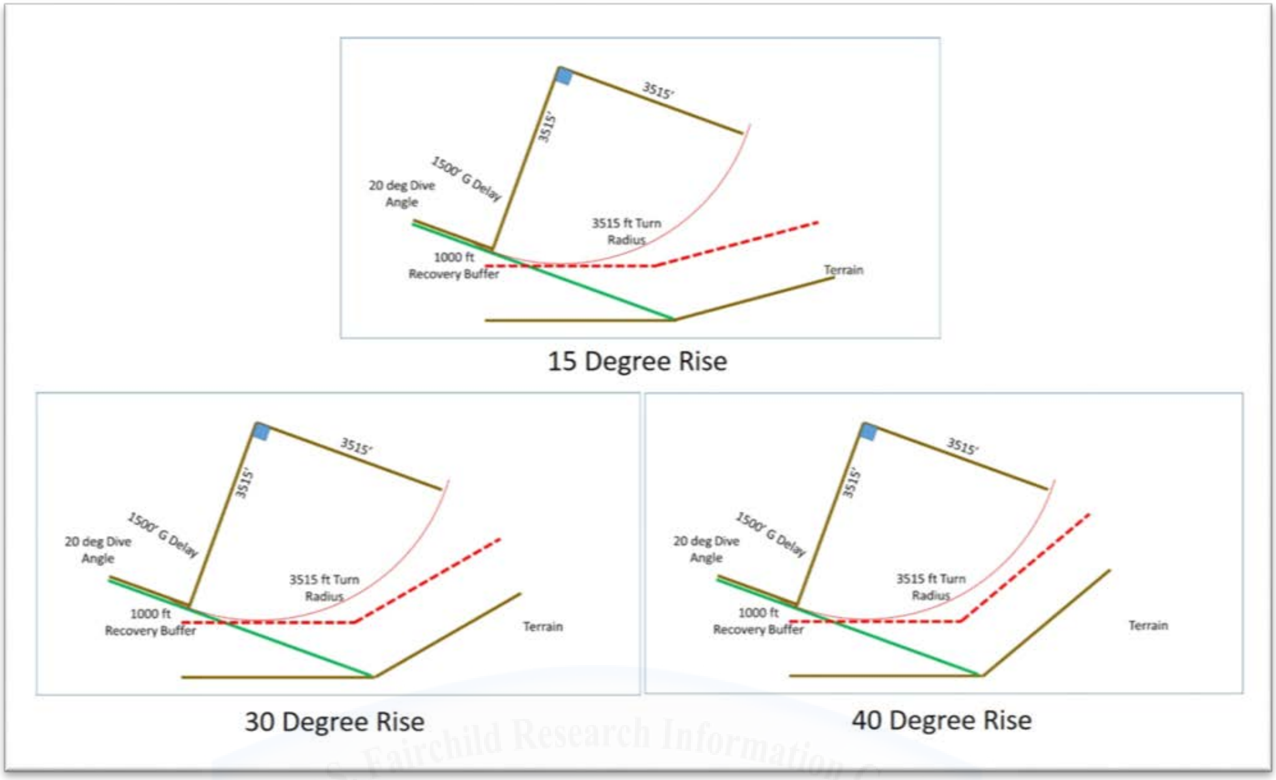


*Figure 8. Shallow on-speed high-angle strafe*

The geometry that results from a fast (480 KIAS in this example) approach varies from the recovery radius (4000 feet in this case) and down track range prior to recovery initiation (2 seconds results in 1600 feet). Despite this, recovery minimums remain unchanged and it is only in the instance of the steeply rising terrain that the pilot even approaches the safety buffer. All shallow attacks appear to provide required recovery altitudes regardless of attack airspeed (Fig. 9).

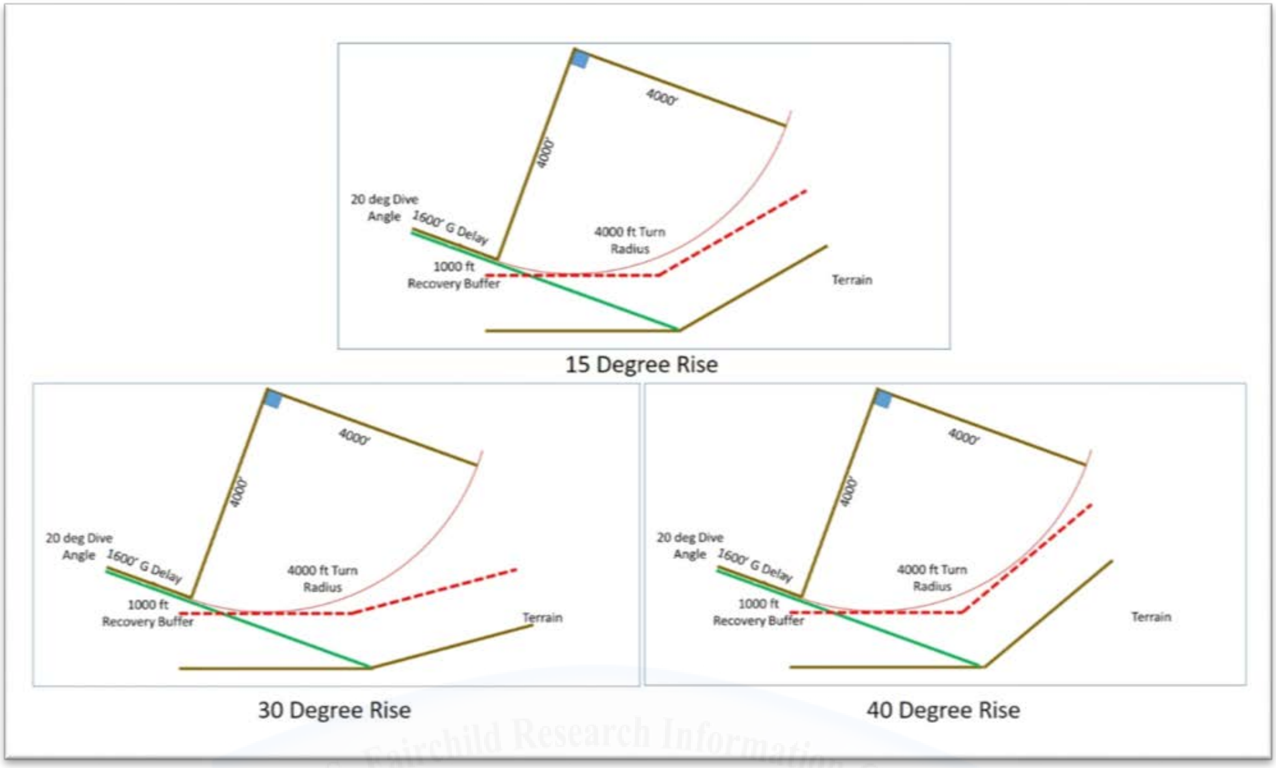


*Figure 9. Shallow fast (480KIAS) high-angle strafe*



A steep and fast high-angle strafe attack results in a recovery that generally passes closer to rising terrain than any other high-angle strafe variant. The combination of the increased depression angle at the initiation of the recovery and the increased radius of 4000 feet result in the pilot pushing the safety buffer over the rising terrain. In the most extreme example, terrain rising at 40 degrees would result in a pilot passing within approximately 500 feet of rising terrain (Fig. 10).

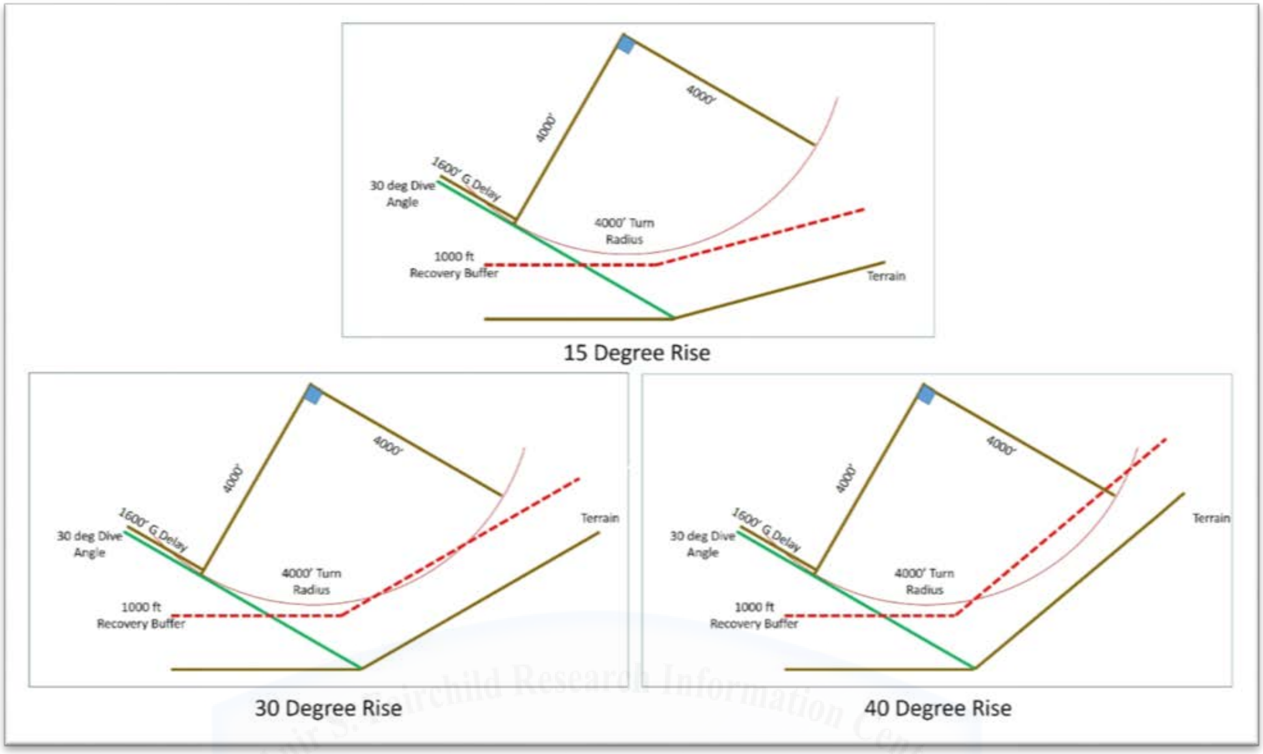


*Figure 10. Steep fast (480 KIAS) high-angle strafe*

## Alternate Analysis

The F-16 community, to some extent, has adopted high-angle strafe as the de facto strafe technique. The argument for high-angle strafe is that it provides a higher safety margin while still achieving weapons effects based on fuze function requirements. An employment range of 7000 feet allows for fuze function and 2 seconds of track time to achieve a satisfactory level of weapons effects. With a normal recovery, the safety margin of 1000 feet provides adequate terrain separation to allow this tactic to be executed across a broad spectrum of scenarios. Coupled with the addition of AGCAS, the argument for high-angle strafe is strengthened with one more safety buffer.

The confidence placed in the safety buffers built into high-angle strafe are misplaced in the event an F-16 pilot is executing in varying terrain. In some circumstances, the analysis demonstrates that this safety buffer was decreased by 50% in rising terrain (of approximately 40 degrees). AGCAS is designed as a last chance safety buffer to protect a pilot in the case of incapacitation. Because air-to-ground strafe is a controlled maneuver that places the aircraft in proximity to the ground, the terrain clearance buffer was decreased to minimize obtrusive fly-ups.[26] With the typical terrain clearance buffer of only 25 feet, the pilot can still put the aircraft in an unrecoverable situation.

When employing in mountainous terrain, low-angle strafe does not provide adequate terrain clearance. AGCAS fly-ups would occur prior to normal low-angle strafe employment ranges. This fly-up could also occur too late to avoid any man-made structures, trees, etc. far of the target. Low-angle strafe is not a suitable tactic to execute in mountainous terrain and for these reasons, a third option is required.



## Hybrid Attack

This analysis demonstrated that when strafing in to rising terrain high-angle strafe tactics still provide a decent level of safety buffer. When executing the standard high-angle attack with 30-degree dive angle and on-speed execution of no more than 450 KIAS, the closes a pilot should expect to pass within rising terrain is exactly at the mandated safety buffer of 1000 feet. If the pilot find himself slightly fast (480 KIAS), he will pass within 500 feet of the rising terrain. In this case, the margin of error is small, and any single execution breakdown such as a late cease-fire/recovery, faster speed (500 KIAS, for example) or a lighter than normal G pull could prove fatal. Perfectly executed low-angle strafe failed to properly provide adequate ground clearance at only 15-degree rise. While these parameters may be rare, could an attack be designed to mitigate the risk of ground collision or AGCAS initiated fly-up?

An example of an attack to consider is a hybrid attack that combines the geometry of both strafe tactics with a trigger on and cease-fire range somewhere at or between both attack types. The first option is to execute low-angle strafe dive angle (5-15 degrees) and strafe at high-angle strafe ranges. This new option will create a sight picture that closely resembles that observed during normal high-angle strafe tactics (Fig. 11). Additionally, clearance is well above the low-angle safety margin during the final attack and remains above the high-angle safety buffer, even in the most extreme terrain rises. The only consideration the pilot must that is that if this type of attack is executed against relatively level terrain short of a rise, it is likely the PGU fuze will impact at too low and an impact angle and velocity to function.



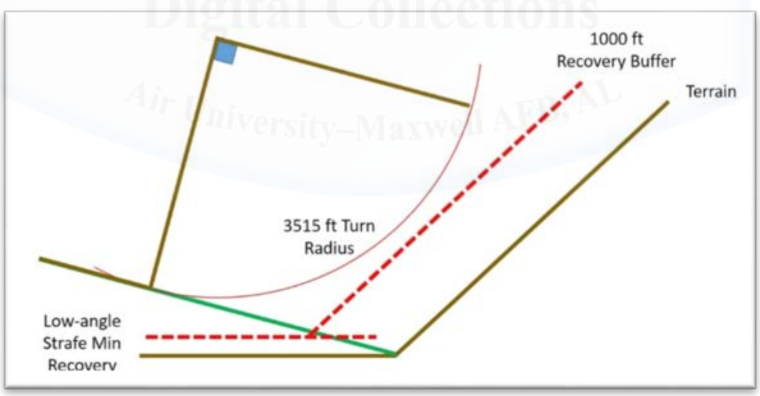


*Figure 11. Hybrid attack*

It is only when the target lies exactly at the intersection of level terrain with the rising terrain adjacent to it that the hybrid attack is lacking (the same has been demonstrated for both low-angle and high-angle strafe). It is in this scenario that fuze function and impact angle may be a concern due to extended shot ranges with lower impact angles. Running a CWDS simulated attack shows initial impact velocity for M-56 series round at a lower than expected fuze function velocity of 942 ft/sec.  The same run show impact velocity well over 1000 ft/sec for PGU series munition.  It is unclear what rate of fuze failures M-56 series munitions would experience, but counter to the concerns with low or high-angle strafe, the safety margin is preserved.  Again, this is only a concern when the target is within 500 feet of the intersection of level and rising terrain.  If this attack is conducted into terrain, the initial attack ground clearance will even exceed normal high-angle strafe safety margin and impact velocity is preserved (Fig. 12).

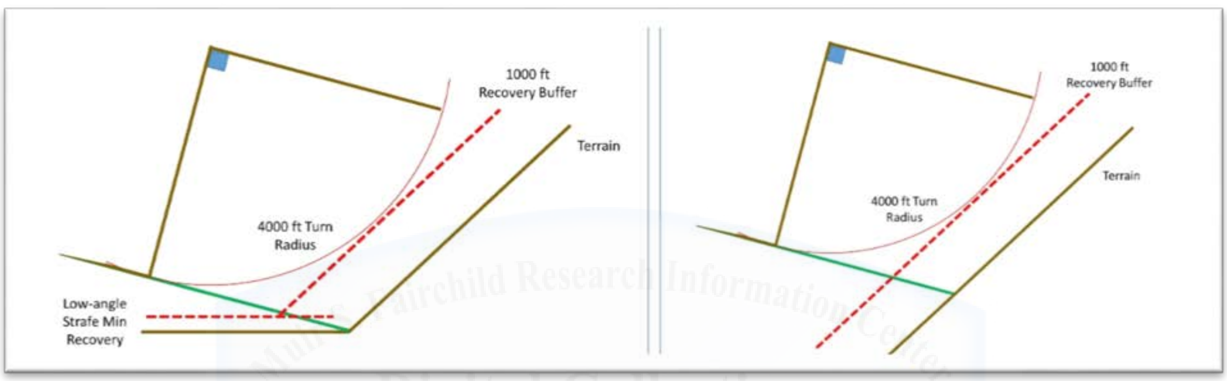


*Figure 12. Hybrid fast and hybrid into rising face*



## Conclusion

### Hybrid Strafe for Guaranteed Safety Margin

In 2007, a tragic incident during Operation Iraqi Freedom that cost the life of an experienced F-16 pilot energized the F-16 community to take a close look at its strafe tactics.  The result, after some number crunching and several iterations, determined that high-angle strafe was the preferred tactic for employing the 20mm cannon.  This attack called for dive angles of 20-30 degrees and a recovery of 1000 feet AGL.  This attack facilitates safe execution with an adequate margin of safety.  Additional OFP updates to the aircraft itself and new targeting pod capabilities added in overcoming limitations with target identification.

Another incident in 2011 was the catalyst to implement AGCAS in DFLCC equipped F-16s. Unrelated to strafe execution, this G-LOC again costs the life of an experienced F-16 pilot. AGCAS is designed to initiate an automatic recovery in the event of predicted ground collision. This system provides an additional margin of safety when executing attacks in proximity to terrain. In normal operation, the system is designed to provide nuisance free operation. In strafe mode, however, to facilitate this operational constrained, recovery can be as low as 9 feet and does not guarantee obstacle clearance.

With the addition of AGCAS, current high-angle strafe TTPs warrant a new look. In level terrain, no changes to the tactic are required. What did require additional analysis was strafe in mountainous or rising terrain. In this scenario, the pilot is presented with steeper than expected sight pictures and recovery requirements. The analysis also demonstrated that low-angle strafe is an unacceptable tactic due to marginal or non-existent recovery buffer above terrain. In cases of moderately rising terrain, low-angle strafe put the pilot on a ground collision intercept that, best case, would initiate fly-up prior to the attack or, worse case, result in ground impact. A fly-up initiated during strafe presents an additional danger sending rounds long of the target since the gun system is not disabled.

High-angle strafe still maintained both ground clearance as well as some level of safety buffer. For on-speed, on-dive angle attacks, the 1000 foot safety margin was only violated when strafing into terrain exceeding 30 degrees (or 1 foot of rise per 2 feet of horizontal distance). In the most extreme cases of terrain rising at 40 degrees with a faster than planned attack, the pilot would pass within 500 feet of terrain (inside currently established safety margin but still short of an expected fly-up scenario). For those reasons, another attack was considered.

This "hybrid" attack calls for low-angle strafe dive angles with high-angle strafe employment ranges.  Undesirable in level terrain due to weapon impact angles and fuze function, the attack is perfectly suited for targets that exist on rising terrain.  By utilizing a 5-15 degree dive, the pilot is presented with a more manageable sight picture and recovery problem.  In all cases (max dive angle and faster than planned attack), recovery meets or exceeds the 1000 foot safety buffer.

## Recommendations

Based on the analysis presented in this research paper, there are six recommendation for the F-16 community moving forward.  These recommendations cover when an F-16 pilot will execute one of three different strafe tactics.  Additionally, there is some further research to be conducted to finalize the viability of these tactics.  Finally, there are recommendations on future OFP implementations.



### 1. Standardize Operation in Mountainous Terrain

Within the contiguous United States, the FAA has designated the Appalachian Mountain Range and the entire Western United States except the San Janquin Valley as "mountainous terrain".  This does little to provide guidance to pilots as neither the FAA nor ICAO designate mountainous terrain outside of the United States.  Air Force instruction provides further guidance and states "In the absence of other MAJCOM guidance, USAF aircrews shall consider as mountainous those areas defined in 14 CFR §95.11 for CONUS, Alaska, Hawaii and Puerto Rico. In other areas, use 500 ft. surface elevation change over a ½ NM."[27]  This guidance may appear clear on its surface, but a pilot might be directed to employ in an unfamiliar area.  As Epperson states, "once airborne, there is little time for fighters to meticulously formulate tactics and then brief the flight prior to execution".[28] Also, the expectation for an F-16 pilot to carry 1-to- 50 terrain charts to cover the entire AOR, and to reference them in-flight to apply 11-202v3 regulation in untenable. In all these cases, the procedures for operating in mountainous terrain technically only apply to IFR flight. Air Force instruction 11-214 covers training rules employment procedures and ground clearance, but does not technically apply in the case of combat operations.

Bottom line, a gap exists for what, if any additional ground clearance procedures must be utilized when employing in mountainous terrain. Therefore, the Air Force must clarify operations in mountainous terrain. First, designate mountainous terrain based on area of responsibility (AOR) in a single reference. Second, publish guidance for any additional restrictions or considerations for employment or visual flight rules operation in mountainous terrain.



### 2. Strafe Attack Selection

With clearly defined classification of mountainous terrain within a given AOR, I pilot can make the correct decision on which method of strafe to utilize. Analysis recommends a hybrid strafe must be utilized when attacking into moderately rising terrain. In instances where the target is located on level terrain, high angle strafe remains the most dynamic option. Finally, if the target is located right at the base of the rising terrain (within 500 feet), high-angle strafe should be executed but the pilot must be cognizant of the terrain far of the target and potentially cease-fire early in extreme cases (terrain rising at 40 degrees or more).

### 3. Gun System Evaluation

The research discovered weapon system evaluations for 20mm functionality is lacking. The 86 Fighter Weapons Squadron routinely conduct Combat Hammer to evaluate fielded air-to-ground weapon systems. These evaluations confirm that fielded weapons systems operate in accordance with designed specifications, and, in some instances, expand employment and operating envelope. There is not data beyond design specification and computer modeling to evaluate the functionality of 20mm fuze.

Combat Archer must open an evaluation of the fuze functionality of HEI 20mm ammunition. This evaluation should include operation at various impact angle and impact velocity. Trials should be run that expand the employment envelope for 20mm until fuze function drops below an acceptable level. This data will support further considerations to design strafe tactics.

### 4. Tactic Validation and Dissemination

The 16th Weapons Squadron at Nellis is the F-16 Weapons Instructor Course squadron. Aside from conduction F-16 weapon officer training, the 16th WPS develops, directs and disseminates F-16 TTPs. The 16th WPS must evaluate the feasibility of the research conclusions presented in this paper in high-fidelity simulators and then on range in a controlled environment. Once validated, the responsibility ultimately lies with the 16th WPS to disseminate an approved and vetted attack option when execution strafe in mountainous terrain.

### 5. New OFP Requirements

Currently, the F-16 is mechanized to provide radar ranging through the air-to-ground strafe reticle and present that range data to the pilot in both raw format and range relationship within the strafe reticle itself. Additional cues can be set by the pilot to aid in determining when to commence firing and cease firing. This symbology is purely based on pilot input ranges and is not dynamic. Dynamic weapon employment zones for in-range are displayed to the pilot for every other weapon (including air-to-air 20mm employment).

Future OFPs should include a dynamic air-to-ground strafe cues. An in-range cue will display to the pilot when the gun can be employed and achieve minimum impact velocity to achieve fuze function and desired weapon effects. A dynamic cease-fire cue will indicate when the attack must be completed to achieve safe ground separation based on a normal 5 G recovery. The in-range cue is calculated purely off dive angle and radar ranging to the target. The recovery cue can be pulled from the AGCAS terrain data.

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