A98-31474

ICAS-98-1,8,3

# APPLICATION OF GROUND COLLISION AVOIDANCE SYSTEM NUISANCE CRITERIA

R. Huffman Jr., Instrumentation Branch Chief
United States Air Force Test Pilot School
Edwards Air Force Base, California

M. Skoog, Chief of Research
K. Prosser, AFTI/F-16 Project Pilot
416th Flight Test Squadron
Edwards Air Force Base, California

L. Piñeiro, AFTI/F-16 Flight Controls Engineer
Air Vehicles Directorate, Air Force Research Laboratory
Wright-Patterson Air Force Base, Ohio

M. Ferm, Aircraft Control Systems Engineer
Aeronautical Systems Directorate, Defense Material Administration
Stockholm, Sweden

## Abstract

The United States Air Force has been actively pursuing ground collision avoidance system technology for the past decade. Despite this effort, controlled flight into terrain remains the number one cause of aircraft loss in the United States Air Force. Research suggests the primary limitation of current ground collision avoidance system technology is the excessive occurrence of nuisance warnings. Pilots quickly learn to "tune out" ground collision avoidance system warnings or turn the systems off entirely to avoid these false warnings. Currently, only one criteria exists to indicate the threshold between valid warnings and those that will be considered nuisances by the pilots. The purpose of this paper is to demonstrate how to apply this criteria to a ground collision avoidance system.

## Background

Controlled Flight Into Terrain (CFIT) is the number one cause of aircraft loss in aviation (Ref. 1). For the past 11 years, the United States Air Force (USAF) has actively pursued the development and use of ground collision avoidance system (GCAS) and ground proximity warning systems (GPWS). Many systems have been developed and fielded including five different systems on the F-16 alone[1]. Of the GPWS that have been fielded, none have failed to meet specification, yet CFIT remains a leading cause of aircraft loss in the USAF. Current GCAS have two limitations that prevent them from significantly reducing the USAF CFIT rate. First, none of the production systems provide protection to the incapacitated or severely disoriented pilot. Second, all of the current systems are plagued by nuisance warnings - warnings that are issued when the aircraft is not in imminent danger of ground impact. As a result, many pilots learn to "tune out" the warnings or turn off the GPWS in order to accomplish the mission. Until recently, no criteria existed to describe the boundary between a warning that pilots consider valid and a warning they would consider a nuisance. The Advanced Fighter Technology Integration (AFTI) F-16 test team recently completed a flight test program to define this boundary. This criteria was applied during the development of the AFTI Automatic GCAS (Auto-GCAS). This paper shows how the criteria can be applied to a generic GCAS design using the F-16 as an example.

## Contributing Elements to Nuisance Warnings

There are five major elements found in ground collision avoidance systems. Each element shares in the nuisance warning budget. A designer must be aware of these elements and do everything possible to minimize the contribution to this nuisance budget.

### Recovery

The first element is the auto-pilot, or in the case of ground proximity warning systems, the ground evasion maneuver which is performed by the pilot. This element is referred to as the recovery for clarity. The

[1] Current F-16 GPWS include: Descent warning after takeoff, Combined altitude radar altimeter Altitude low (CARA ALOW), Mean sea level (MSL) Line in the sky, Ground Avoidance Advisory Function (GAAF), and Predictive Ground Collision Avoidance System (PGCAS)

recovery is a scripted maneuver that pulls the aircraft away from the impending obstacle. A good recovery is predictable and aggressive. The recovery can drive nuisance warnings if it is not as aggressive as what the pilot expects. The key element of a good recovery is pilot acceptance.

Recovery Prediction Algorithm

Directly related to the recovery is the recovery prediction. The prediction of the recovery projects the current aircraft state forward in time to determine if the aircraft is approaching danger. The prediction is the driver for recovery initiation (or warning in manual systems). AFTI flight tests have resulted in the belief that nuisance determination is made at recovery initiation - regardless of the minimum approach to the terrain. Errors in the prediction tend to be put on the conservative side to avoid ground impact. Such conservatism can initiate a recovery so early that it is considered unwarranted.

Terrain Database

Surrounding obstacles are represented to the ground collision prevention system with an elevation database. The elevation database also provides information to terrain referenced navigation systems. The critical features of the elevation database are accuracy and resolution. Nuisance warnings are created when gross errors occur in the database in very small areas as shown in Figure 1.

A designer has little control over the database accuracy and resolution. Where this element of the collision prevention may be the largest source of errors currently, it is continually improving. Therefore, the best strategy to eliminating nuisances is to build flexibility into the elevation database. The system design should include the flexibility to be updated with improved databases.

Navigation Solution

To obtain an accurate position on the elevation database, a terrain referenced navigation (TRN) system is usually employed. A TRN is a Kalman filtering scheme which correlates terrain slopes with slopes around the position in the elevation database. This scheme is made robust by combining inputs from other navigation sources like an inertial platform, or Global Positioning System. The navigation system's key features are accuracy and estimated uncertainties. Errors in navigation can result in warnings given for terrain that is not along the aircraft's true flight path. Likewise, no warning may be given for real terrain. To avoid the later, designers typically smear the elevation database based on estimated uncertainty. Mountain peaks become plateaus and valleys are narrowed as navigation uncertainty increases. Such conservatism contributes to the nuisance potential. Note: terrain database accuracy and navigation accuracy are factors for stored terrain GCAS systems. An active sensor could replace these in which case sensor resolution and accuracy would have a similar contribution to nuisance warnings.

System Interface

The final element to a ground collision avoidance system is the interface with the pilot. The warning of imminent collision with terrain should be unambiguous and command the pilot's attention.

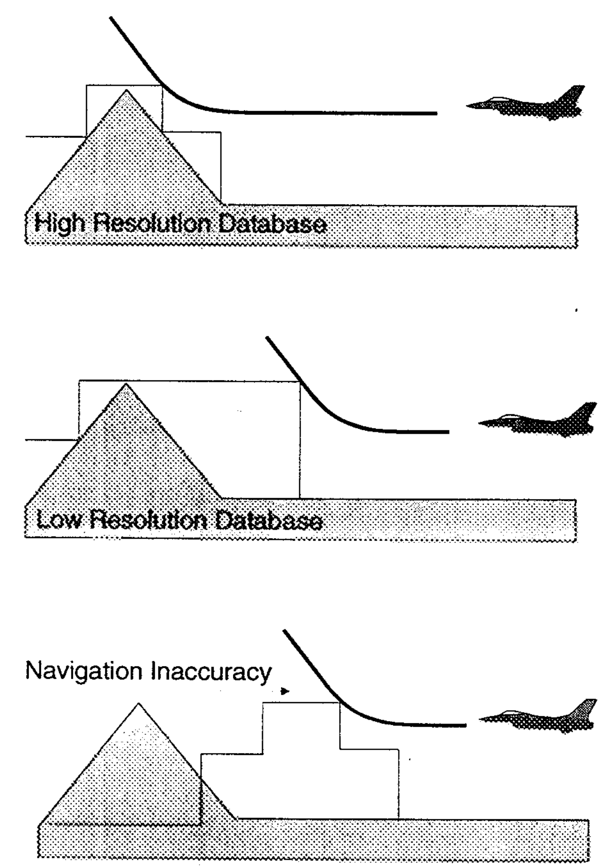


Figure 1. Database Effects

Nuisance Criteria

The nuisance criteria testing was accomplished in 1997 over the course of 33 flights. The results indicated that the potential for nuisance correlates to aircraft state/ground closure rate and pilot anxiety at

Table 1. - Anxiety Ratings

| ***Rating*** | ***value*** |
|---|---|
| Was never more than casually aware of ground proximity. | 1 |
| Would have felt comfortable with a recovery at a lower altitude. | 2 |
| Recovery went as anticipated. | 3 |
| Recovery went lower than personal comfort levels allow. | 4 |
| Sensations of life threatening conditions. | 5 |

recovery initiation. The tests measured pilot anxiety with the subjective rating scale presented in Table 1. Ground closure rate based on the aircraft state at initiation was mapped into the Time Available to Ground Impact (Tagi). The flight test results are depicted in Figure 2 (Ref 2). A boundary was chosen at 1.5 seconds based on the lower bound of the anxiety 3 and 4 ratings. This 1.5 second limit represents the entire nuisance budget. Recovery aggressiveness, recovery prediction, terrain database, and navigation accuracy all eat into the 1.5 second total. If the total exceeds 1.5, nuisance warnings are likely to occur. The designer's goal is to keep the sum of all errors below 1.5 seconds.

<u>Application of the Criteria</u>

Nuisance criteria is predicated on pilot acceptance. The cornerstone to measuring nuisance potential is the determination of an aggressive recovery. An aggressive recovery is a straightforward procedure which the pilot would perform when evading collision with the ground. The maneuver is most often described as a roll to wings level and pull the nose of the aircraft above the horizon. The definition of the aggressive recovery model is based on the performance characteristics and operational environment of the airplane. In manual warning systems, the recovery must be intuitive and natural to avoid unnecessarily long pilot reaction time. An automatic recovery system (auto-pilot) has an advantage in this respect since pilot reaction time is not a factor.

It could be summarized that handling qualities are of little importance. However, this assumption is not

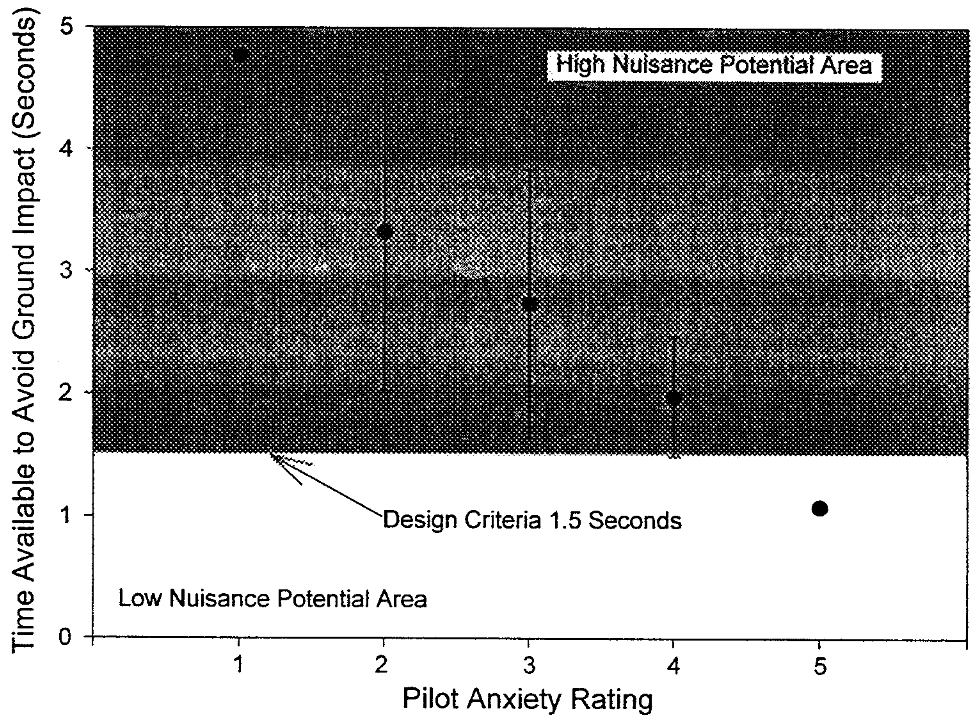


Figure 2. - Nuisance Criteria

accurate. The key to a useful collision avoidance system is pilot acceptance and confidence. Pilots are not enamoured with the idea that GCAS is taking control of the aircraft. This situation is aggravated when the auto-pilot performs a ground evasion maneuver contrary to the method a pilot would employ. Additionally, since a pilot is without some situational awareness when a recovery initiates, an abrupt recovery will only add uncertainty. Automatic systems have the advantage of protecting incapacitated pilots. However, if an over aggressive recovery is employed, it will only serve to further injure or disorient the pilot.

The development of the recovery model could be universal if it was defined as the maximum capability in roll rate and loading capability. In most fighter aircraft, the pilot will not perform a recovery using this maximum performance which could severely constrain the warning system design. Since pilot perceptions are the key to measuring nuisance warnings, the recovery model must be developed with pilot input.

As an example, the F-16 Predictive Ground Collision Avoidance System originally assumed a 4g recovery. During flight test it was found that this recovery was not considered aggressive enough. This non-aggressive recovery contributed to instances of nuisance warnings. The recovery was later changed to a 5g recovery to more accurately represent the pilots perception of an aggressive recovery.

Design Application

With the recovery maneuver determined for the specific airframe, the designer can now apply the criteria to the GCAS under design. This is done in two stages. The first stage generates a family of curves that can be compared against the GCAS initiation altitudes for various flight conditions. The second stage of criteria application evaluates GCAS initiation altitudes generated from a batch or real-time simulation. The following paragraphs detail this process.

Modeling the aggressive recovery

The first step in applying nuisance criteria to a GCAS in the design stage requires a modeling of the "aggressive recovery" maneuver. As mentioned above, the definition of the "aggressive recovery" maneuver is usually comprised of a g/angle-of-attack target with some g-onset. The roll axis is typically defined by airframe rollrate (P) capability versus airspeed (Vc). Some control logic is required to gently approach wings level. This is usually a simple gain applied to bank angle. We will use the F-16 as an example to illustrate this.

For the F-16, a 5g recovery was deemed aggressive for most of the flight envelope. At slower speeds, angle of attack limiting was required. For the case of our simplified model, a simple g versus airspeed algorithm was developed to limit the available g at slower airspeeds. For bank angles greater than 90 degrees, a -1g push was desirable. g-rate was always limited to 4g's per second in all cases. In equation form this looks like:

$$
\begin{aligned}
&If\,|\phi| > 90^\circ then\\
&g_{target} = -1\\
&Else\\
&g_{target} = f(Vc)\\
&EndIf\\
&\dot{g} = \max\left(g_{rate}, |g(i) - g_{target}|\right) \times \Delta t\\
&g(i+1) = g(i) + \dot{g} \times signum(g_{target}) \times \Delta t
\end{aligned}
$$

For the F-16 example the roll axis targets a rollrate (P) of 100 degrees per second or two and a half times the bank angle (ϕ) (whichever is smaller). Roll acceleration was not factored into the aggressive recovery. In equation form this looks like:

$$
\begin{aligned}
&P = -2.5 \times \phi\\
&P = \max\left(P, 100(\text{deg/sec})\right)\\
&\phi(i+1) = \phi(i) + P \times \Delta t
\end{aligned}
$$

This recovery model for the F-16 has been validated through flight test on the AFTI/F-16. The recovery has been initiated over 1,900 times and evaluated by 30 different pilots. To date, the auto-pilot has been unanimously judged as aggressive.

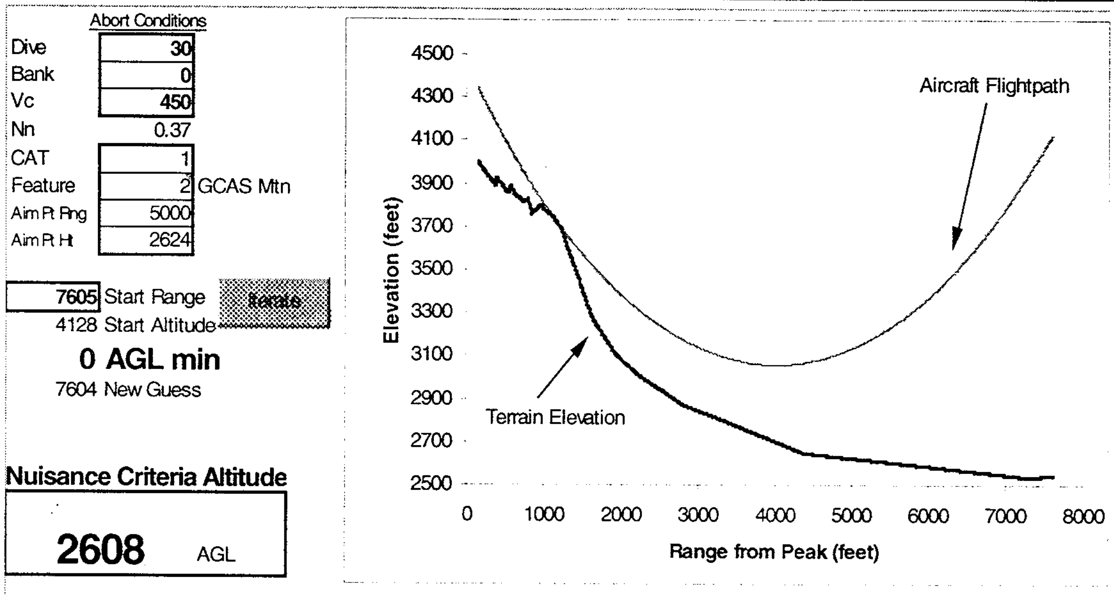


Figure 3. - F-16 Aggressive Recovery Simulation

Pre-algorithm limit plots

With the recovery modeled, a family of curves can be generated for use in evaluating a GCAS algorithm. Determining the altitude lost from various initial flight conditions (plus one and a half seconds of altitude loss at those same initial flight conditions) generates the family of curves. For example, from a 30 degree dive with wings level at a velocity of 800 feet per second, the model estimated 3000 feet of altitude would be lost (Pt. A on Figure 5). A 30 degree dive at 800 feet per second generates 400 feet per second of descent rate. The boundary for nuisance warnings would be at 3600 feet (or 3000 + 400 * 1.5). A GCAS that issued a warning higher than 3600 feet AGL for this condition (over flat terrain) is nuisance prone at that condition.

An example of the output from a working model is presented in Figure 3. This figure shows the nuisance boundary determined for a specific terrain feature. The terrain feature used here is a vertical obstacle 1,500 feet high. The recovery example is a 30 degree dive at 0 degrees bank and 450 knots calibrated airspeed, initiated 7,605 feet from the peak at 4,128 feet above sea level. This recovery intersects the terrain at around 1,100 feet from the peak. Unlike the smooth terrain calculation, vertical velocity is not used when applying the 1.5 second nuisance criteria buffer. For this case the velocity at initiation orthogonal to the recovery flightpath at the minimum approach to the terrain feature must be used. Figure 4 illustrates this. Because there is a 26.7 degree climb at the minimum AGL point in the recovery, there is an effective 56.7 degree approach to this point when the 30 degree dive at initiation is added in (26.7 + 30 = 56.7). By backing up the 1.5 seconds from the initiation point, the criteria boundary is at 5,136 feet above sea level (an initiation elevation of 4,128 feet + 804 feet per second velocity at initiation * cosine(56.7 degree approach) = 5,136 feet). The range that corresponds to this elevation is 8,267 feet from this terrain feature.

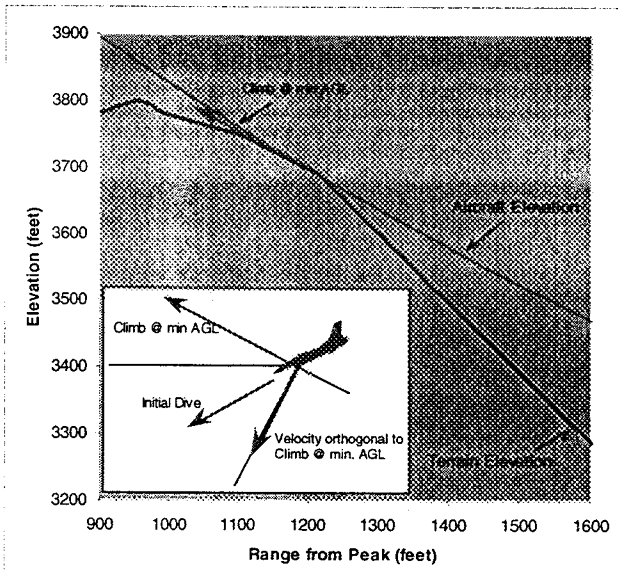


Figure 4. Velocity Orthogonal to Minimum AGL

For the F-16 example, Figures 5 and 6 show the nuisance boundaries for various dive and bank angles.

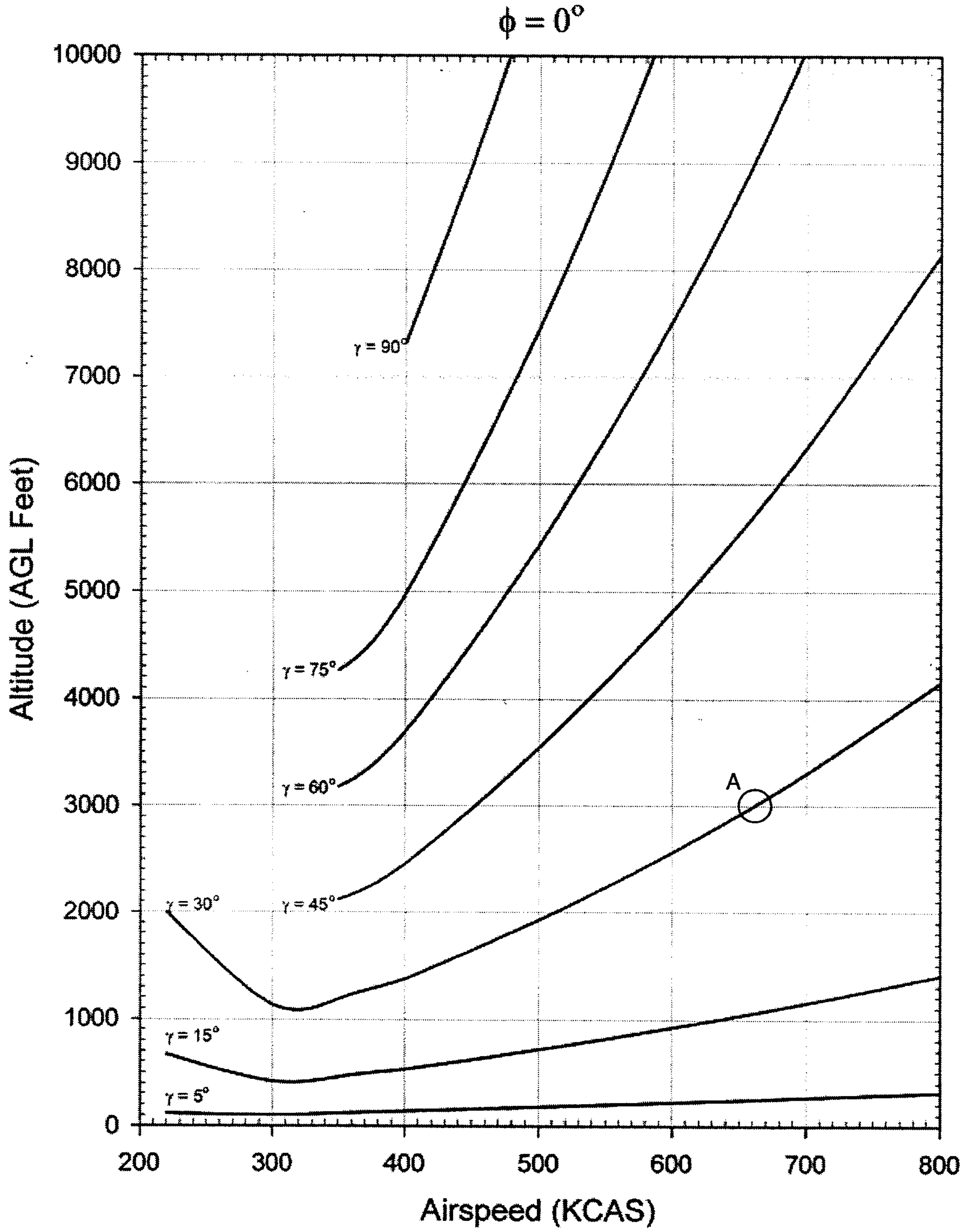


Figure 5. – F-16 Nuisance Altitudes, Wings Level

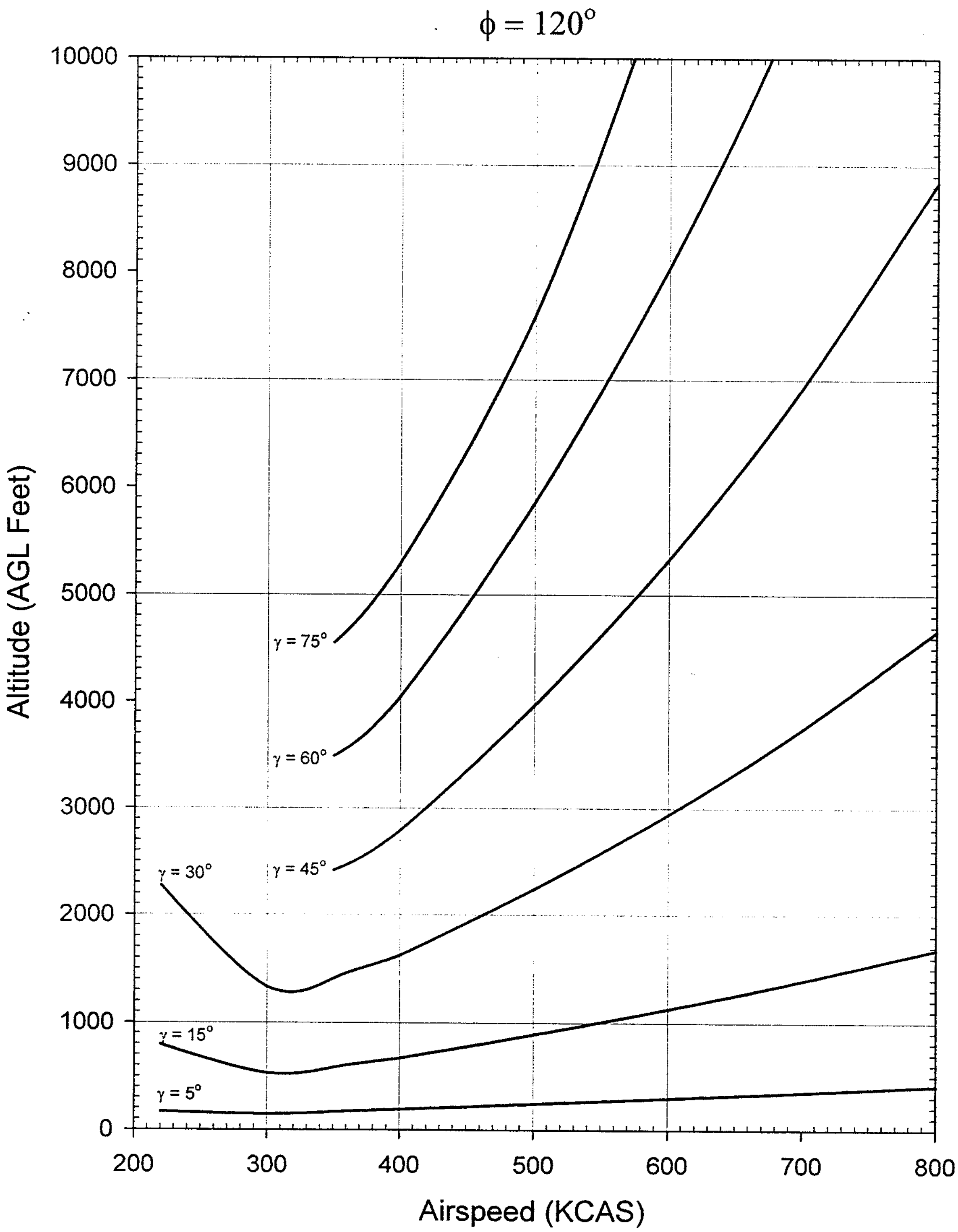


Figure 6. – F-16 Nuisance Altitudes, 120 Degrees Bank

Table 2. - GAAF Nuisance Comparison

| ***Dive Angle (degrees)*** | ***Bank Angle (degrees)*** | ***Airspeed (KCAS)*** | ***GAAF Warning Altitude (Feet)*** | ***F-16 Nuisance Altitude (Feet)*** | ***Nuisance Predicted?*** |
|---|---|---|---|---|---|
| 30 | 0 | 450 | 1769 | 1645 | Yes |
| 5 | 0 | 500 | 210 | 180 | Yes |
| 15 | 120 | 400 | 1011 | 671 | Yes |
| 10 | 0 | 250 | 308 | 241 | Yes |

We can now evaluate any F-16 GCAS. As an example, we will evaluate the F-16's GAAF system. Table 2 presents GAAF warning altitudes and corresponding nuisance criteria boundary altitudes from the above figures for four different conditions.

The above table suggests that the GAAF system is prone to nuisance warnings and operational experience has confirmed this. At this point the designer should examine each element of the nuisance budget to identify the primary driver of the nuisance warning (see page 1). In the case of GAAF which is a flat earth system, the likely cause is an overly conservative pilot reaction time assumption or the 4g recovery used which, as already discussed, has been considered not aggressive enough by pilots.

Post design evaluation

The above evaluation is useful early in the design phase for evaluating static conditions, but does not take into account all of the real-world dynamics. The effects of conditions such as roll-pitch coupling, nose slice at elevated bank angles, and elevated load factors at initiation are best evaluated with a batch or real-time simulation.

Following the development of a batch and real-time simulation, nuisance criteria can again be applied. As warnings are generated in the real-time simulation, conditions at initiation should be trapped off. These initiation conditions become initial conditions for a model of the aggressive recovery. The starting point for this recovery simulation is extrapolated forward from the warning initiation until a point where the recovery simulation intersects the terrain. The amount of time taken to extrapolate the initiation point to terrain intersect is the time available to avoid ground impact. If this value exceeds 1.5 seconds, a nuisance potential exists.

## Conclusions

Nuisance Criteria in and of itself is a viable tool for the successful design of a ground collision avoidance system. The criteria provides a logical, pilot oriented, method of bounding recovery initiations. Although the application presented here ultimately used altitude boundaries, these boundaries were derived from a time pad rather than an arbitrary altitude pad. This time pad is a more direct representation of the pilot's cognitive process when assessing the need for initiating a recovery.

Determination of criteria boundaries is possible during the initial stages of a GCAS design. All airframe specific information is available for the criteria early in the design phase. This information consists of g versus angle-of-attack, maximum safe angle-of-attack, g-onset, and roll rate characteristics.

Pilot confirmation of an aggressive recovery is essential. Without an aggressive recovery, the nuisance potential of a GCAS cannot be determined using this criteria. The inherent determination of nuisance in a GCAS is pilot perception. This preconceived notion of the capabilities of the aircraft must be captured in the definition of the recovery maneuver.

Data collected to date concerning nuisance criteria has focussed on high performance fighters. Testing should be conducted to validate the application of this criteria for heavy airframes. In theory, aircraft performance should be irrelevant to the 1.5 second recovery buffer defined in this criteria. Aircraft performance is captured in the definition of the aggressive recovery maneuver.

## References

1. Boeing Marketing and Safety Data, in Aeronautical Safety Investment Council Meeting, held by National Aeronautics and Space Administration, Seattle, Washington, 25-26 March, 1997.

2. Prosser, K. et al., *The Development of Nuisance Warning Criteria for Ground Collision Avoidance Systems: Preliminary Findings*, The Proceedings of the Society of Experimental Test Pilots, Society of Experimental Test Pilots, Lancaster, California, September, 1997.

3. Yamaguchi, S. et al., *F-16 C/D Block 40 Avionics Development and Integration Flight Test Evaluation Volume 1*, AFFTC-TR-93-18, AFFTC, Edwards AFB, California, July 1996.