

**DEVELOPMENT OF AN ACCEPTABILITY WINDOW
FOR A GROUND PROXIMITY AVOIDANCE SYSTEM**

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ABSTRACT

A Ground Proximity Warning System (GPWS) is a software algorithm that draws appropriate parameters from different aircraft sensors, in order to calculate the necessary altitude, based on aircraft configuration, for a safe recovery. When the calculated recovery altitude is overestimated, false alarms (also referred to as nuisance warnings) tend to occur, influencing the pilots to lose confidence in the system. When the calculated recovery altitude is underestimated, however, certain ground impacts become unavoidable. Defining what is acceptable to the pilots has been a difficult task. In support of the Air Force's Systems Program Office (ASD/SD), the Crew Station Design Facility has developed such a window for the F/FB/EF-111 aircraft, which is based on pilots' subjective evaluations. As part of an overall evaluation of the F/FB/EF-111 GPWS, subjective data were collected following the completion of each of a multitude of different configurations flown in an FB-111 simulator and analyzed using the multiple regression technique. The window of acceptability was developed using the minimum recovery altitude as a function of vertical velocity. Finally, the window was validated using performance data collected during the overall evaluation of the GPWS.

INTRODUCTION

Between 1970 and 1984, the statistics for combined Air Force and Navy accident mishaps related to Controlled Flight Into Terrain (CFIT) have involved approximately 400 aircraft and many human lives (DiPadua, Geiselhart, Gavern, and Lovering, 1988). The installation of a forward looking Terrain Following Radar (TFR) as means of warning the pilot of a possible ground impact would greatly reduce the number of mishaps. However, such a solution may be prohibitively expensive and would make the aircraft more susceptible to detection by enemy radars. A Ground Proximity Warning System (GPWS) on the other hand, while not as reliable as a forward looking TFR, may be a cheap and simple solution. In 1976, the Federal Aviation and Administration mandated the use of a GPWS on commercial airliners. The algorithm was mainly designed to promote safety in final approach. Since that period, the number of commercial CFIT accidents has dropped to virtually zero (Orr, Geiselhart, and DiPadua, 1987). In the case of commercial aircraft, the algorithm need not be extremely sophisticated. In the tactical and strategic

environments, however, such simplicity may be unacceptable. Highly maneuverable aircraft will be operating in a totally different regime than the commercial and some wide body military transports, thus requiring a GPWS algorithm that will function consistently in low level missions, over diverse terrain.

In general, GPWS systems rely on a software algorithm with the appropriate parameters being drawn from existing aircraft sensors, to present the pilot with an emergency warning that requires immediate reaction before ground impact. The algorithm calculates the required recovery altitude based on aircraft configuration. When present altitude becomes less than the calculated recovery altitude, plus an additional buffer, an emergency warning is presented to the pilot which will require immediate reaction to avoid ground impact. When the calculated recovery altitude is overestimated, false alarms (also referred to as nuisance warnings) tend to occur and the pilots lose confidence of the system. On the other hand, when the calculated recovery altitude is underestimated, certain ground impacts become unavoidable. The design philosophy of a GPWS is that:

(1) if a pilot does not commit a ground clearance error, he should never receive a warning to pullup (otherwise considered to be a nuisance warning or a false alarm).

(2) if he receives a warning, the pilot may be assured that he has committed a ground clearance error.

The ability of the designer to minimize nuisance warnings should be reflected not only in the potential strength and reliability of the GPWS, but more importantly in the crew members' confidence level in the system.

While other efforts have attempted to develop such a window based on the laws of aerodynamics, the present effort is examining the problem from a different perspective. An attempt is being made to develop the window of acceptability based on pilots' subjective ratings for recoveries accomplished in an FB-111 simulator, in response to a GPWS warning. This window of acceptability would then serve as a tool for measuring the level of nuisance warnings of a proposed GPWS for the F/FB/EF-111 aircraft. This effort is part of an overall evaluation of the proposed F/FB/EF-111 GPWS performed in support of the F/FB/EF-111

METHOD

Subjects

Four Strategic Air Command (SAC) and four Tactical Air Command (TAC) pilots participated in the evaluation. An attempt was made to insure that the pilots were representative of the overall population by varying the age and the level of flying experience. The age of the pilots ranged from 27 to 49 with a mean of 34, and a standard deviation of 9 years. F/FB/EF-111 operational flying experience varied from 150 to 1800 total hours, with a mean of 910 and a standard deviation of 609 hours. The sample of pilots represented four United States Air Force bases: Plattsburg, Mountain Home, McClellan, and Canon.

Procedure

Prior to flying the FB-111 simulator, the pilots were given the desired aircraft parameters (based on roll angle, flight path angle, airspeed, and wing sweep) for each particular test trial. The experiment simulated flying in the weather without an outside-the-window visual scene. However, a Head Up Display (HUD) was presented as an aid to the pilot, allowing him to place the simulator in the desired flight path angle condition without performing major mental calculations in translating from dive angle to flight path angle (The FB-111 does not currently employ a HUD). The pilot's responsibilities included:

- (1) establishing the given parameters for wing sweep, airspeed, roll angle, and flight path angle.
- (2) attempting to stabilize and maintain the simulator at 1 G until the GPWS warning was initiated.
- (3) recovering to climbing flight.

Each test trial was terminated when the flight path angle of the simulator became greater than the angle of the terrain slope. The pilots were instructed to perform the following recovery procedure:

- (1) Roll to wings level (+ 20 degrees).
- (2) Pull to 5 Gs or 14 degrees Angle of Attack (AOA).
- (3) Roll and pull simultaneously.

The decision for selecting these criteria for Gs and AOA was based on the design of the algorithm. As a means of compensating for gravitational force feedback, a light located on the right caution panel would illuminate at 4 Gs or 12 degrees AOA, while a second light would follow suit at 6 Gs or 16 degrees AOA. The pilots were also instructed to focus on the G and AOA

indicators. All trials, throughout which the aircraft exceeded a maximum of 6 Gs and/or 18 degrees AOA, were reflown by the pilot. At the completion of the recovery maneuver, each pilot was reminded of the initial aircraft configuration and provided with feedback on the maximum Gs, maximum AOA, and the minimum recovery altitude. The pilot was thereafter asked to subjectively rate this minimum recovery altitude based on a five point scale (1=too high, 2=slightly high, 3=about right, 4=slightly low, and 5=too low).

In an attempt to decrease pilots' reaction time performance biases (an anticipatory situation where the pilot knew he would eventually receive a pullup warning that required immediate recovery), two additional factors were introduced. Throughout all the test trials, background communication was simulated by playing an audio tape of a combat mission, recorded during the Vietnam war, and transmitted to the pilot through the headset. Furthermore, four distractor voice caution messages, with a lower priority level than the GPWS warning, were randomly presented to the pilot during the initial configuration setup window. These voice messages were Autopilot, Autopilot Failed, Alpha, and Alpha Side Slip. The pilots were instructed to ignore both the background communication and the distractor voice messages, which were irrelevant to the performance of the test trial.

Each pilot flew eight practice trials, followed by three sets of 48 experimental trials, with a 15 minute break after the first set of trials and a one-hour lunch break after the second, for a total of 144 test trials. The distractor caution messages were presented to the pilot at an average of 10 seconds, with a standard deviation of five seconds.

Design

Four independent variables were manipulated throughout the experimental trials. These were Roll Angle (0, 30, and 60 degrees), Flight Path Angle (-5, -10, -20, and -40 degrees), Airspeed (350, 475, and 600 Knots), and Terrain Slope (0, 6, 12, and 18 degrees). Of these four variables, only Airspeed and Flight Path Angle were of interest to the present effort. For each airspeed condition, a different wing sweep configuration was flown. The airspeed/wing sweep combinations were 26 degrees of wing sweep for the 350 Knot condition, 45 degrees for 475 Knots, and 55 degrees for 600 Knots. These airspeed/wing sweep combinations were considered standard flying configurations. It should also be noted that, due to the handling characteristics of the FB-111 simulator, the 350 Knot airspeed condition included flight path angles of -5, -10, -20, and -30, while the 475 and the 600 Knot airspeed conditions included flight path angles of -5, -10, -20, and -40.

Minimum clearance altitude (also referred to as the minimum recovery altitude) and vertical velocity were considered as the primary variables of interest. The overall experimental design was

comprised of a single run per condition/per pilot for a total of 144 test trials per pilot (3 roll angles X 4 flight path angles X 3 airspeed conditions X 4 terrain slopes).

Pilots' subjective ratings on a scale from 1 to 5 -- 1 being too high, and 5 being too low -- of the minimum recovery altitude for each of the 144 test trials, were analyzed using the linear regression analysis technique on each of the five ratings.

Apparatus

Facility. The study was conducted at the Crew Station Design Facility (CSDF), which is a U.S. Air Force simulation facility that belongs to the Aeronautical Systems Division (ASD) of Air Force Systems Command. The CSDF government personnel are assigned by the Crew Systems Division, Human Factors Branch (ASD/ENECH). The facility is used to perform human engineering experiments and system mechanization evaluations in support of a variety of System Program Offices.

Simulator. The FB-111 simulator included such major components as the control loading assemblies, seats, canopies, and visual window. An Advanced Simulator Technology interface cabinet was mounted on the nose of the cockpit to interface the simulator with the Systems Engineering Labs' computer complex. A walkway with railings was installed around the simulator to insure pilots' safety and allow for easy access in and out of the cockpit. The majority of the instrumentation on the left side of the cockpit were available to the pilot. The FB-111 software package contains all flight, engine, atmosphere, weights, and balances modules, along with a dictionary of all FB-111 data variables, and several other specific commons and datapools. All Linear Function Interpolation curves were validated. A simple HUD, shown in Figure 1, was designed to aid the pilots in placing the simulator in the desired flight path angle configuration. The HUD also displayed a horizon line indicating ground level.

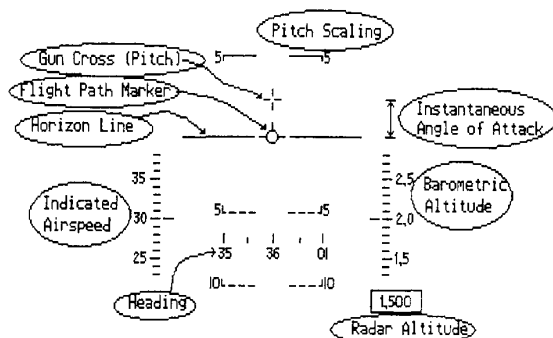


Figure 1. Head Up Display used in the experiment

Experimenter's Console. The experimenter's console was located approximately 12 feet away from the simulator. It included a complete intercom system, together with communication to and from the pilot inside the simulator. The console's displays duplicated the simulator's HUD, instruments and displays, and were used to monitor the pilot's performance. Furthermore, the console's controls permitted the experimenter to start, stop, and reset the simulation at any time.

Computer Complex. The simulator is connected to a series of large and small computer systems. This computer complex includes five Gould series 32/7780, one Gould concept 32/8780, two PDP 11/34, three PDP 11/35, and two Silicon Graphics Iris Computer Aided Design Stations.

Voice Message Unit Mechanization. One warning and four caution voice messages were presented to the pilot's headset through the intercom channel. The five messages included Pullup, Alpha, Alpha Side Slip, Autopilot, and Autopilot Failed. In order to maintain consistency across subjects and conditions, pilots were told not to change the volume control setting. The warning message (Pullup) was mechanized in such a way that it was continuously presented to the pilot until the corrective action was completed. The warning was presented in message pairs (Pullup/Pullup) with an inter-message interval of 500 milliseconds and a delay of three seconds before the next pair of Pullup messages. The caution messages, on the other hand, were also presented with an inter-message interval of 500 milliseconds, except that the messages were only repeated twice. These caution messages, Alpha, Alpha Side Slip, Autopilot, and Autopilot Failed, were mechanized in such a way that they would not be presented if the GPWS warning was within 100 feet of becoming active.

Audio Systems. The voice messages were recorded on an Amiga micro computer by a female employee of the CSDF. The employee, who had a distinctive and mature mid-western voice, presented the messages in a formal and impersonal manner. The Amiga used a high speed voice digitizer (Future Sounds), with a sampling rate of 10,000 samples per second, to convert the messages from analog to digital format. The Amiga was thereafter connected to the main frame computers using an RS-232 interface, and transmitted the messages to the pilot's headset (an ASTROCOM model number 20680 with MX-2508/A/C pads) through the intercom channel. The length of time it took to articulate the Pullup message was approximately 420 milliseconds.

Background communication was simulated by an audio tape on a Panasonic tape player, model number RS-263AUS, and transmitted to the pilot's head set through the intercom channel.

RESULTS

Pilots' rating data were divided into five

separate data sets and analyzed independently using the linear regression analysis technique. Minimum clearance altitude and vertical velocity were considered the main variables. The five ratings corresponded to the five statements found in Table 1. The regression analyses described the relationship between minimum clearance altitude as a function of vertical velocity for each of the ratings, by calculating the correlation coefficient and the function of each line.

TABLE 1. Rating criteria for each minimum recovery (or clearance) altitude.

MINIMUM CLEARANCE ALTITUDE

1. TOO HIGH
2. SLIGHTLY HIGH
3. ABOUT RIGHT
4. SLIGHTLY LOW
5. TOO LOW

Figure 2 contains the minimum clearance altitude as a function of vertical velocity for each trial's recovery altitude subjectively rated by the pilots as a 1 (too high). The subsequent Figures (3, 4, 5, and 6) describe the data compiled from the other four ratings. Overall high correlation coefficients indicate a strong relationship between the two variables of interest.

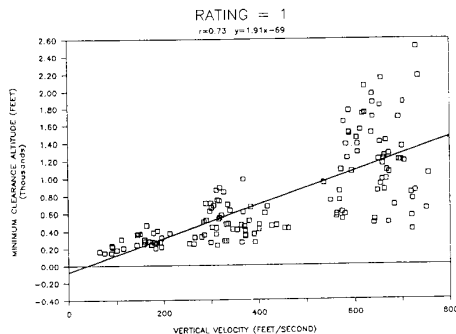


Figure 2. Minimum clearance altitude as a function of vertical velocity for pilots' subjective rating of 1 (too high).

However, an inspection of Figure 7, representing the functions of each of the five ratings calculated by the regression analyses, suggested that while a distinction exists between ratings 5, 4, 3, and (1 or 2), no sensitivity was demonstrated by comparing ratings 1 versus 2. A one-way ANOVA confirmed what was seen in Figure 7. Therefore, ratings 1 and 2 were combined to form a new set of data, which is shown in Figure 8.

The combined function line from the two highest ratings (1=too high and 2=slightly too high) was defined as the boundary for the highest

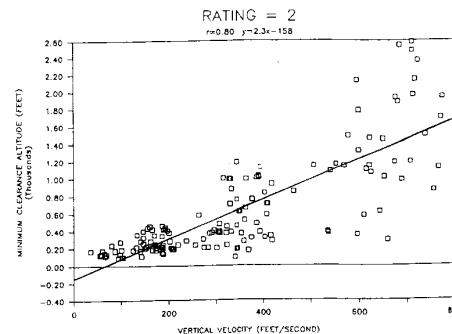


Figure 3. Minimum clearance altitude as a function of vertical velocity for pilots' subjective rating of 2 (slightly too high).

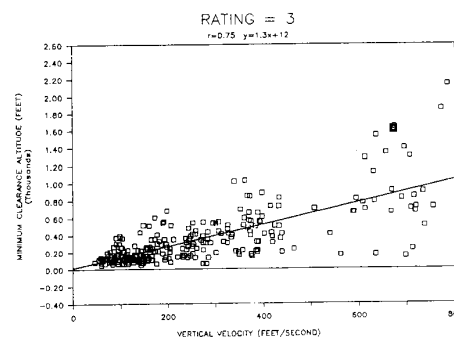


Figure 4. Minimum clearance altitude as a function of vertical velocity for pilots' subjective rating of 3 (about right).

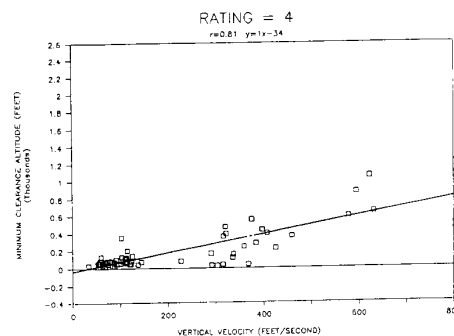


Figure 5. Minimum clearance altitude as a function of vertical velocity for pilots' subjective rating of 4 (slightly low).

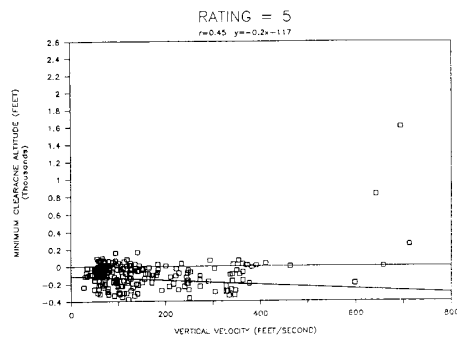


Figure 6. Minimum clearance altitude as a function of vertical velocity for pilots' subjective rating of 5 (too low).

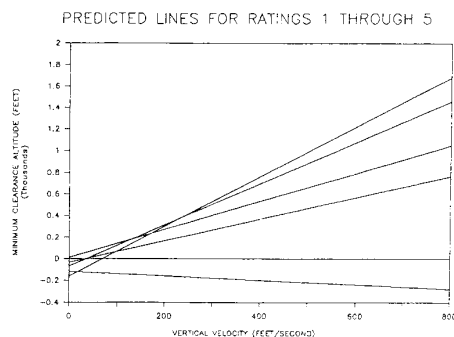


Figure 7. Predicted function lines for minimum clearance altitude as a function of vertical velocity for pilots' subjective ratings of 1 through 5.

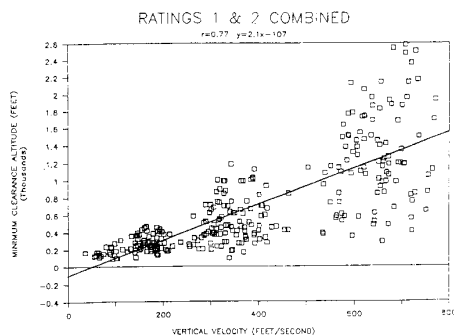


Figure 8. Minimum clearance altitude as a function of vertical velocity for pilots' subjective ratings of 1 and 2 combined.

acceptable recovery altitude based on the pilots' subjective evaluation. The function line representing "slightly too low", or rating 4, was considered the breakpoint for the lowest acceptable recoveries and was designated the lower boundary of a pilots' subjective window of acceptability for GPWS recovery altitudes. Both function lines were corrected in such a way that their zero-intercept points were at a recovery altitude of zero feet (as opposed to a negative value), and no minimum clearance altitude would be lower than 50 feet. Any minimum clearance altitudes that fall between the two boundaries would consider the GPWS warning to be a "good" one, while values on top of the upper boundary would be considered false alarms. Any recovery altitudes below the lower boundary of the window would be considered "too close for comfort." This proposed window of acceptability is shown in Figure 9.

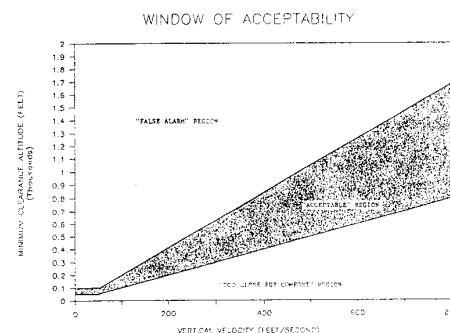


Figure 9. Pilots' Window of Acceptability based on pilots' subjective ratings.

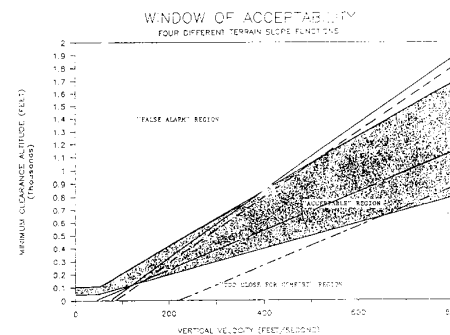


Figure 10. Function lines from the four terrain slope conditions overlaid on top of the Window of Acceptability.

In order to validate this acceptability window, function lines of pilots' performance data, sorted by the four terrain slopes (0, 6, 12, and 18 degrees), were calculated and plotted against the window. These data were collected in support of the overall GPWS evaluation (Hassoun & Barnaba, 1989). An inspection of Figure 10, which contains the performance data overlaid on top of the window, indicated that better than 90 percent of the recovery altitudes for terrain slope of zero fell within the acceptable window. Furthermore, terrain slopes of six and 12 degrees were acceptable for vertical velocities between 175 and 400 feet per second. At vertical velocities less than 175, the warnings appeared to be initiated too late, while at greater than 400 feet per second the GPWS warnings were considered to be a nuisance. Finally, in accordance with the 18 degree terrain slope performance data analysis (Hassoun, 1989), the majority of the GPWS warnings were initiated too late for an acceptable minimum recovery altitude.

DISCUSSION

This window should prove useful to the designers of the algorithm, in that it graphically describes the trend of the data and makes it obvious as to which areas need additional development. Furthermore, the window will provide the System Program Office engineers with the opportunity to pre-set an acceptable false alarm rate on a GPWS algorithm, and the ability to test the proposed design of the algorithm by applying performance data collected through man-in-the-loop simulations, or even off-line simulations, to the window of acceptability.

The window of acceptability should be further developed by increasing the number of pilots participating in the evaluation, in order to provide a more representative subjective acceptance of pilots to GPWS warnings, and the warnings' relationships with minimum recovery altitude and vertical velocity. Furthermore, a larger sample of pilots would allow the evaluation of the window at higher order coefficients, in an attempt to compare the application of first versus second order coefficients to the development of the window, and deciding upon which would be more representative of the F-111 pilots?

There remains many questions that cannot be answered by the current support effort. One critical area of interest involves the usage of such a window in the evaluation of GPWSs on other aircraft (such as the F-16). Can we generalize from the present results, or should a new set of data be collected on each individual aircraft? What about different pilot populations? The main argument of such a discussion is related to the fact that the response characteristics of different aircraft are not the same (for example, F-111 versus F-16). Furthermore pilots tend to react differently based on the type of aircraft they are flying. A comparison of F-111 and F-16 pilots would prove to be a useful evaluation in answering such concerns.

Another area of interest is the level of sophistication that could or should be exhibited by a GPWS algorithm. Current efforts have improved upon the older less sophisticated systems, which historically assumed that the world was perfectly flat all around, by attempting to predict and calculate the slope of the terrain and account for it in their calculations. Other efforts have focused on using a digital data base covering the terrain being flown over. Further research efforts, which have not been approached yet, should attempt to develop different algorithms for the type of mission or mode that the aircraft is currently flying. This type of information is currently available and could be obtained from the aircraft's own on-board computer.

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