Development and Flight-Test of a Commercial Head-Up Display

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1 INTRODUCTION

Most military aircraft utilize HUDs, often as the primary flight display (e.g. F-16, F-22, C-17). So what is the big deal about putting HUDs on civil transports? The answer to this lies in the fact that military and civil requirements are significantly different. Military HUDs provide primarily tactical information to assist pilots to maneuver the aircraft and fire weapons without looking inside the cockpit. There is little emphasis on landing aids. The primary role of the civil HUD is to enhance the safety and capability for takeoff and landing with less emphasis on cruise flight. The differences and similarities between civil and military HUDs are summarized in Table 1.

Table 1 Comparison of Primary Requirements for Civil and Military HUDs

REQUIREMENTS	CIVIL	MILITARY
Eyes Out of Cockpit	Yes	Yes
Weapon Delivery	No	Yes
Situational Awareness in All Attitudes	Yes	Yes
Low Visibility Landing (Cat IIIa – 600 RVR and 50 ft DH)	Yes	No
Low Visibility Takeoff (300 RVR)	Yes	No
Precise Glideslope control for Visual Approaches	Yes	Yes
Tailstrike Protection	Yes	No
Improved Airspeed Control	Yes	No

The primary role of the civil HUD is seen to be the enhancement of approach and landing and takeoff capability in conditions of very low visibility.

The pilot's view through the BAE Systems HUD for a Cat IIIa landing is shown in Figure 1.

Figure 1 Low Visibility Landing – 300 RVR and 50 ft Decision Height

There is a difference in philosophy between the airline users of HUD. Some airlines are using HUDs as primary guidance for Cat IIIa and do not have the autoland option installed, whereas others use the HUD as a monitor for the Autoland.

BAE Systems, previously Marconi Avionics, has a long history as a leading manufacturer of Military HUDs, and decided to get into the commercial market in 1997. Because of the significant differences in the functional requirements noted in Table 1, the symbology and control laws used for military HUDs do not apply to civil HUDs. This paper describes the flight-testing and simulation work involved in starting with a clean sheet of paper to a certified Cat IIIa HUD. This HUD is currently installed in Boeing 737-800 aircraft operated by major airlines throughout the world. Because the HUD provides guidance as well as symbology, it has been termed the Visual Guidance System or VGS.

The basic design philosophy for the VGS symbology and control laws was to maximize the inputs from the pilot user community. Specifically this meant incorporating airline pilots as an integral part of the design team. This was accomplished by developing the symbology and control laws on a PC Simulator program that could be flown in real time, and taking that simulation to the airline customer bases. As might be expected, many diverse opinions resulted.

Nonetheless, it was possible to develop a symbology set that satisfied the majority of pilots. Several of the airline pilot team members were given an opportunity to fly the symbology in our test aircraft before the design was frozen.

2 OBJECTIVES OF VGS

The objectives established by BAE Systems, in coordination with the launch customer, American Airlines, were very aggressive.

- Cat IIIa capability in all possible aircraft configurations and flight conditions.
- All approved landing flap settings (15, 30 and 40 degrees)
- Autothrottles on or off to touchdown
- One engine failed
- Maximum landing altitude (8,400 ft)
- Flare guidance for all landings with or without ILS
- Tailstrike protection on takeoff and landing
- Low Visibility (300 RVR) Takeoffs
- Takeoff and rollout guidance at all runways with a localizer
- Safe operations in heavy turbulence and windshear
- Recovery from unusual attitudes

No HUD has ever been certified to these stringent conditions, so a considerable amount of flight-testing and simulation was necessary to develop the necessary symbology and control laws. The highlights of this testing are discussed in this paper.

3 OVERVIEW OF FLIGHT TEST PROGRAM

The initial testing and validation of the HUD hardware, symbology, and control laws was accomplished on a 737-200 test aircraft. The installation of the VGS in the 737-200 cockpit is shown in Figure 2.

While this was not exactly a state of the art cockpit, it was more than adequate to accomplish the initial integration, and symbology and control law development for the target aircraft, a Boeing 737-800, which had just been certified and was not available for HUD development. Flight testing with the 737-200 aircraft was initiated in September of 1998. This test program consisted of 93 hours of flight time, and 170 HUD landings that were accomplished in 28 sorties at a wide variety of airports and conditions. Initial sorties were flown in benign conditions to test and refine the control laws and symbology. A primary goal of the HUD was to lower pilot workload in difficult conditions. Therefore, a great deal of emphasis was placed on stressing the system. This included landings in 35 knot crosswinds at night with no navaids, and approaches in a major storm at Crescent City California, near the California-Oregon border.

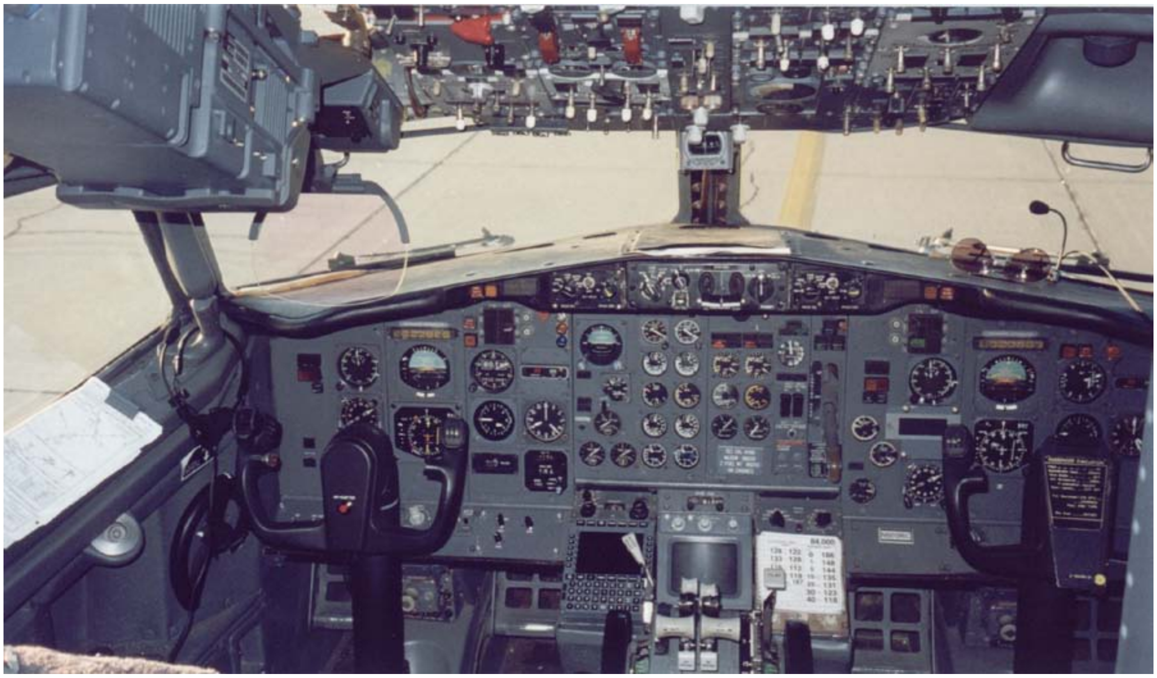


Figure 2 BAE Systems VGS Installed in Boeing 737-200

Once it was established that system was sufficiently robust, the testing progressed to the Boeing 737-800 aircraft shown in Figure 3.

Figure 3 Boeing 737-800 Test Aircraft

A total of 76 sorties were flown in this aircraft, which included 494 landings and 202 hours of flight time. This included the final optimization of the HUD symbology and control laws under a wide variety of conditions. Figure 4 shows the VGS installation in the Boeing 737-800.

Figure 4 VGS Installation in Boeing 737-800

The program philosophy was to go well beyond the minimum requirements for FAA certification, and to flight-test the HUD in the most severe conditions possible. This included:

- 35 knot crosswinds
- 45 knot headwinds and 10 knot tailwinds
- Speed abuses of 30 kts above and 10 kts below Vref.
- Frequent evaluations and system refinements in moderate turbulence and windshear.
- Testing at high altitude airports in strong winds and turbulence.
- Pilot abuse cases (evaluation pilot intentionally introduces a large deviation from the ILS and then follows the HUD guidance to touchdown).

An important part of the flight-test program was to identify airports that included a wide range of conditions, and were not so busy as to preclude flight-test operations. The primary test airports were:

- Atwater airport in Merced (KMER) - old Castle Air Force base – smooth air, long runway, not much traffic – Good ILS.
- Victorville (KVCV) – Old George AFB – lots of wind and turbulence – Good ILS
- Mojave (KMHV) – Winds, turbulence, no ILS, sloped runway.
- Bakersfield (KBFL) – Noisy ILS
- Spokane (KGEG) for runway slope
- SeaTac (KSEA) for cliff at end of runway (only early Sunday mornings – otherwise too busy)
- Oakland (KOAK) for seawall at end of runway
- Crescent City (KCEC) for short runway, high winds, windshear, and turbulence during winter storms.

The FAA certification test flights were accomplished in the launch customer's aircraft, an American Airlines Boeing 737-800. The FAA certification test flights consisted of 17 sorties with 5 FAA pilots. These flights included 149 HUD landings, 25% of which were in simulated zero-zero conditions. The certification test flights were accomplished at the full range of c.g. travel, with autothrottle on and off, at high altitude airports (Colorado Springs and Cheyenne Wyoming), with simulated engine failures, and with all possible landing flaps settings from 15 to 40 degrees. Finally, there were 13 simulated 0/0 takeoffs and 7 takeoffs with simulated engine failure above and below V1.

The FAA Certification process also included a very extensive piloted simulation program. This was conducted on the Boeing Multi-Purpose Engineering Cab or M-Cab. This consisted of 1100 piloted landings in varying winds and turbulence, sensor errors, varying runway lengths and slopes, and varying aircraft weight, c.g., and flaps. Statistical Monte-Carlo analyses were accomplished on the approach and touchdown data to ensure that the HUD met the ILS tracking and touchdown footprint requirements of FAA Advisory Circular 120-28D (Reference 1). 75% of the simulator landings were made in 600 RVR and 25% with simulated 0/0. 176 of the simulator landings were made at an airport elevation of 8400 ft. 92 landings were made with one engine out and 149 with the autothrottle engaged to touchdown.

In spite of taking all possible precautions, including leaving the gear down for some circuits, the program was very hard on tires. This was exacerbated by the fact that the owner of the leased aircraft would not allow touch and go landings. Rapid tire wear was common, and on one landing, the left main gear tires blew out on touchdown, Figure 5. Ironically, this was an autoland, not a manual landing with the HUD. After this event, the gear was left down for essentially all landings while in the pattern to cool the tires. The standard takeoff call for closed circuits became “positive rate, gear down”.

Figure 5 Blown Tires – Too many landings and not enough cooling

4 HUD SYMBOLOGY

The starting point for the civil HUD design was the BAE Systems (formerly Marconi) F-16 HUD symbology. However, airline customer pilots indicated that they wanted symbology that more closely matched the head down primary flight display (PFD). The PFD for the Boeing 737-800 is shown in Figure 6.

Figure 6 Head Down Primary Flight Display – Boeing 737-800

The primary features of this display were incorporated into the HUD design, resulting in the symbology shown in Figure 7.

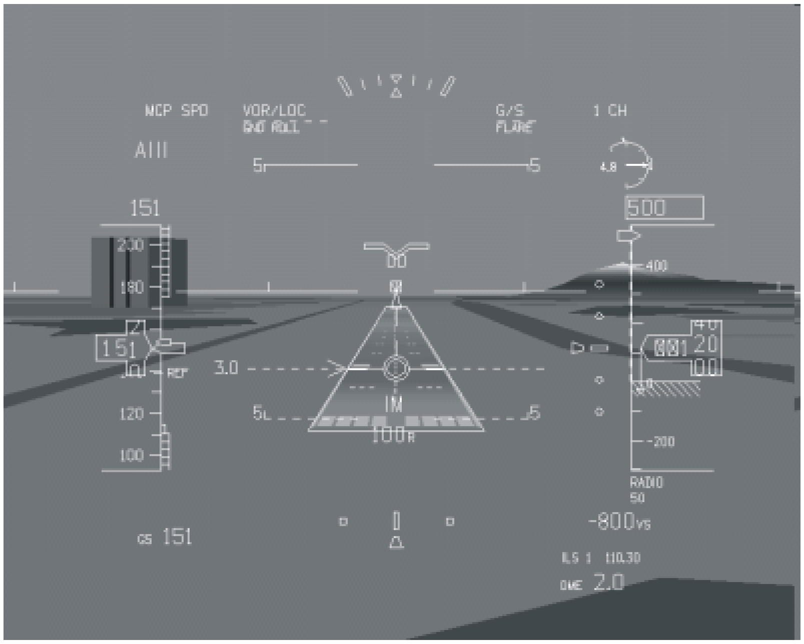


Figure 7 Baseline VGS Symbology (Normal Display Mode)

This symbology retains the essential features of the PFD that include analog displays of airspeed and altitude in the form of large vertical tapes, with imbedded digital readouts. As with the PFD, all autopilot and flight director mode annunciations are displayed across the top of the combiner, and the raw data localizer and glideslope information is shown in the same location as the PFD.

Past HUD research at NASA Ames resulted in symbology for low visibility approaches that consisted of an all-digital format similar to that shown in Figure 8.

Initial simulations followed this lead, by using the vertical tapes for up and away flight, and switching to the digital format on final approach, for low visibility approaches. However, airline pilot evaluators indicated a preference for staying with the tapes all the way to touchdown, and found switching displays on final approach to be distracting. Simulator and flight-testing showed that when presented with the ability to use either symbology format, most pilots chose to fly with the analog tape display for all phases of flight.

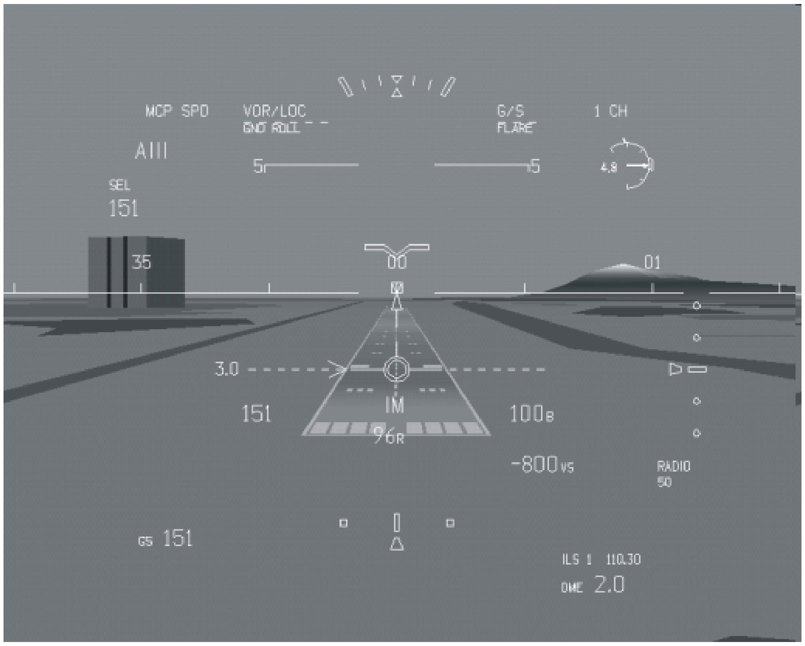


Figure 8 Digital Display Format (VGS Declutter Display Mode)

The final solution was to allow the pilot to select either display format at any time via a button on the combiner unit. The analog display is therefore termed the Normal Display Mode, and the digital display is called the Declutter Display Mode. Flight experience on the line has shown that the normal display mode is used almost exclusively. The only exception is that the declutter mode must be used in large crosswinds. That is because the airspeed and altitude tapes restrict the lateral movement of the flight path symbol when the aircraft is in a large crab angle relative to the runway.

5 SYMBOL DYNAMICS

The HUD display contains a great deal information. However, there are a few key symbols that enhance the ability of the pilot to fly the aircraft in a way that cannot be achieved with head down displays. These are the flight path vector (FPV), acceleration caret, and airspeed error tape as shown in Figure 9.

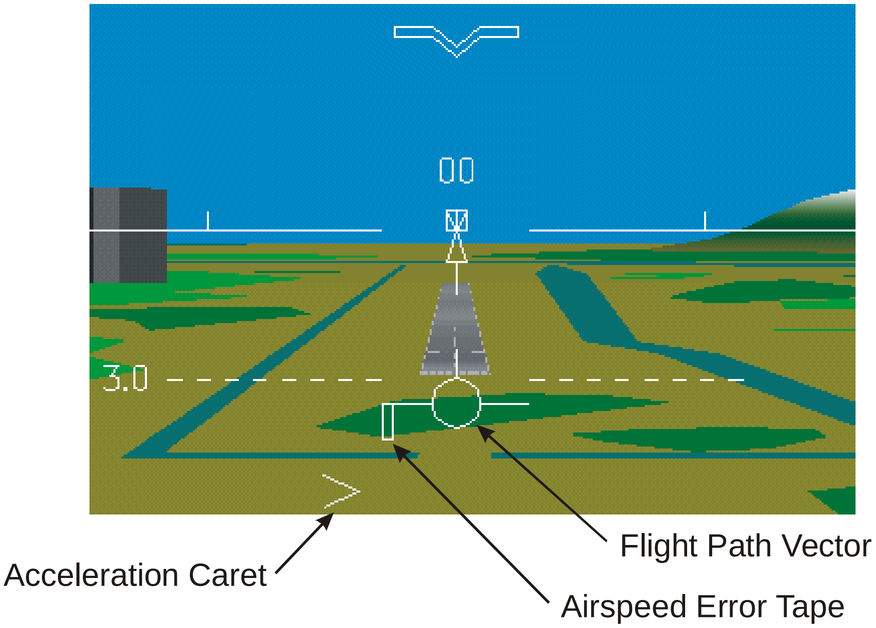


Figure 9 Key HUD Symbols

The flight path vector symbol provides instant information on where the aircraft is going. In the above figure, it is clear that the aircraft will land short unless a correction is made. The acceleration caret symbol is based on inertial acceleration. If the caret is held even with the left wing of the FPV, the acceleration along the flight path is zero. If the acceleration caret is below the wing of the FPV (as shown in Figure 9), the aircraft is decelerating. Finally, the airspeed error tape indicates the difference between the selected airspeed and the current airspeed. In this illustration, the actual airspeed is less than the selected airspeed. Through the use of these symbols, it is possible to maintain very accurate glidepath and airspeed control.

Initial piloted simulations in strong turbulence and windshear indicated some deficiencies. These were not showstoppers, and it was determined that the symbology would be certifiable without modification. However, it was decided that the VGS symbology should be as good as possible in turbulence and windshear where it is most needed. The identified problem with each symbol and the solutions to those problems are discussed below.

5.1 Flight Path Vector Symbol

The problem with displaying raw flight path to the pilot is that the flight path vector significantly lags pitch attitude. This lag makes it difficult for the pilot to make aggressive and precise corrections. For example, in Figure 9 the pilot task is to rapidly move the FPV up to the runway without overshoots. On a turbulent day, this becomes a continuous closed-loop tracking task. This is a high workload task if there is a significant lag in the FPV symbol. The lag between pitch attitude and flight path is given as:

$\frac{\gamma}{\theta} = \frac{1}{T_{\theta 2} s + 1}$ Where $T_{\theta 2}$ is approximately 1 second for most transport aircraft.

It is common to add some pitch-rate to compensate for this, so that the FPV symbol dynamics are described by:

$Y_{FPV} = \gamma_{c.g.} + l_x q$ (where q is pitch-rate and l_x is a distance from the c.g.)

This helps, but the lag in flight path is still apparent when making approaches in strong turbulence. The flight test operation was conducted out of Mojave airport, where turbulence and strong winds are the norm, especially in the winter. It was not uncommon to return from a day's testing to 40 kt winds with gusts to 50 kts. Since Mojave has no ILS, the FPV symbol was especially useful in making approaches in these conditions. However, controlling the FPV precisely and aggressively was a problem. The solution to that problem was to compensate the FPV with washed-out pitch attitude.

$$Y_{FPS} = \gamma_{c.g.} + \frac{l_{xICR} q}{V_{TAS}} + (K_{\theta FPS} \frac{s}{s + \omega_\theta})\theta$$

The first two terms in this equation represent the flight path response at the aircraft instantaneous center of rotation (ICR). With this control law, the FPV responded like pitch attitude at high frequency and like flight path at lower frequencies. Now, keeping the flight path symbol on the touchdown zone became a pitch-attitude tracking task, which was found to be very acceptable.

There was initial concern that this would cause the FPV symbol to become too active in turbulence. However, this was not found to be a problem. In fact, it was an enhancing feature in that a large excursion in the FPV means that flight path is soon to follow, and an aggressive correction is appropriate. Just to be sure, one sortie was conducted to Crescent City in the 737-200 aircraft, when a major winter storm blew ashore. Multiple ILS approaches and landings were conducted to a 5000 ft runway. The direct crosswind at 500 ft was over 50 kts, which sheared to a quartering 25 kt crosswind at touchdown for most approaches. The turbulence below 400 ft could be described as moderate to severe. While the entire flight test crew got airsick, the response of the FPV was clearly validated as the way to go. This was further verified with numerous approaches in turbulence with several evaluation pilots at the Victorville and Mojave airports in the Mojave desert.

5.2 Pursuit Guidance

One significant problem with head up displays is that the flight director and flight path symbols can become overly active in turbulence. In such cases, both symbols tend to “float around the display”. This can result in the pilot “tunneling in” and losing situational awareness. In an attempt to minimize this problem, a pursuit guidance algorithm was developed, in addition to the more conventional compensatory tracking flight director guidance. A fly-off between these algorithms clearly indicated that the pursuit guidance was superior, both in terms of pilot workload, and accuracy of glideslope tracking.

The concept of pursuit guidance is best understood if the guidance cue is thought of as a ghost aircraft that is on the glideslope at a fixed distance ahead of our aircraft as shown in Figure 10a. The small circle inside the flight path vector is the flight director or guidance cue. This cue represents the position of the ghost aircraft on the HUD display. In Figure 10a, we are looking straight down the velocity vector at the ghost aircraft.

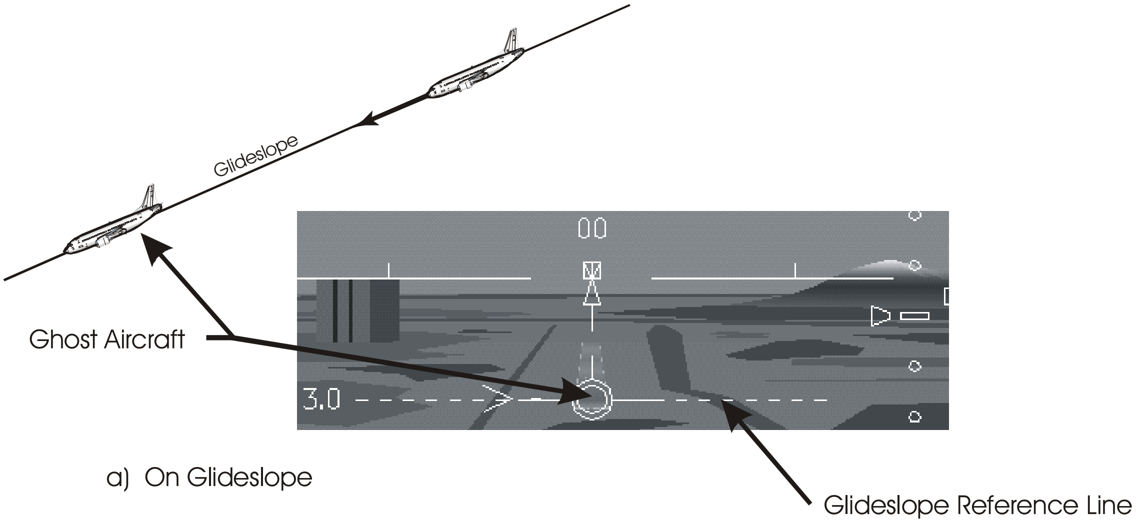
In Figure 10b, our aircraft is below glideslope. The guidance cue deflection away from the dashed glideslope reference line is the angle between our flight path and the ghost aircraft (GSE in Figure 10b). The guidance cue deflection away from the glideslope reference line is directly proportional to the displacement of our aircraft from the glideslope. Even in severe turbulence, the aircraft displacement from glideslope occurs at relatively low frequency. Therefore, the guidance cue (ghost aircraft) tends to be very stable. Once the HUD evaluation pilots learned to focus on the guidance cue as a point of reference, the effect of turbulence became less of a distraction. Also, since the guidance cue is a direct measure of glideslope error, the need to scan to the raw data glideslope is eliminated and situational awareness is more easily maintained.

Interestingly, the advantage of pursuit guidance was not obvious in the Boeing M-Cab simulator. While the RMS tracking errors were a factor of three better than normal compensatory guidance, the pilot workload was moderate. However, in flight-test the pilot workload was noticeably reduced with pursuit guidance, especially when flying in turbulence. It is believed that this discrepancy is due to feel system lags and possibly a lack of adequate motion cueing in the simulator.

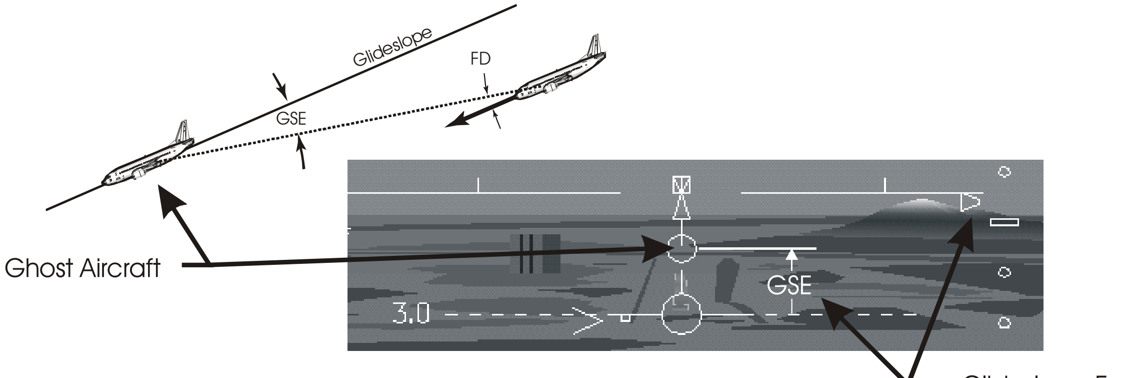
The pursuit guidance approach to flight director control laws was originally developed at the NASA Ames research center by Richard Bray and Gordon Hardy. To our knowledge, this is the first application of that technology to an operational aircraft.

5.3 Acceleration Caret

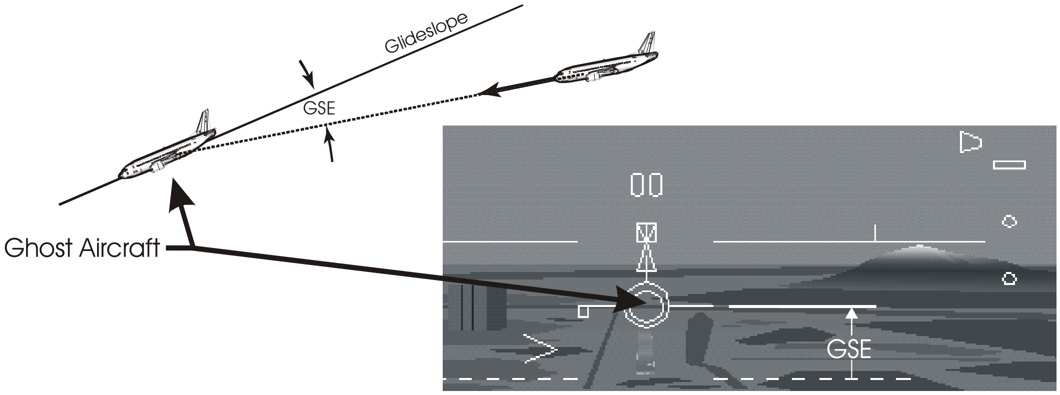
As developed and tested by NASA, the acceleration caret is pure inertial acceleration. The problem with this is that in a strong windshear, the caret results in reverse sensing with respect to airspeed. For example, in a decreasing headwind shear, the airspeed decreases rapidly, but the groundspeed increases. The increasing groundspeed causes the inertially driven caret to indicate that the aircraft is accelerating, which encourages a reduction in power. This is not a good idea since airspeed is already low. The commonly used solution is to remove the acceleration caret in a strong windshear. This is exactly counter to our objective of assisting the pilot in demanding high workload situations.



a) On Glideslope



b) Below Glideslope and Flying Parallel



c) Below Glideslope and Correcting

Figure 10 Illustration of Pursuit Guidance

The solution was to develop a complementary filter so that the acceleration caret symbol has the dynamic response of airspeed at mid-frequency and inertial acceleration at low frequency. In addition, some throttle input was added to account for the lag in engine response. This is illustrated in Figure 11.

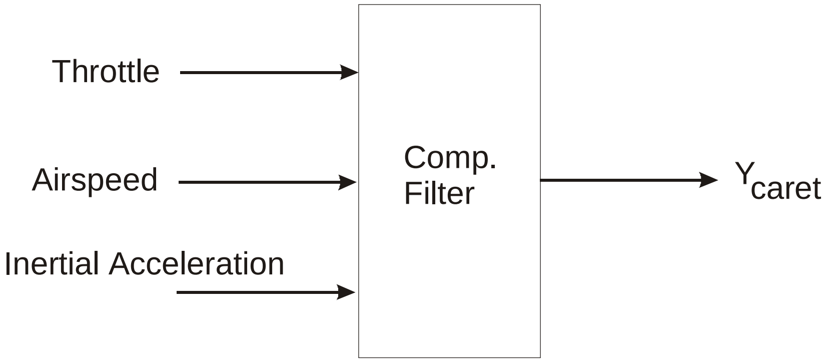


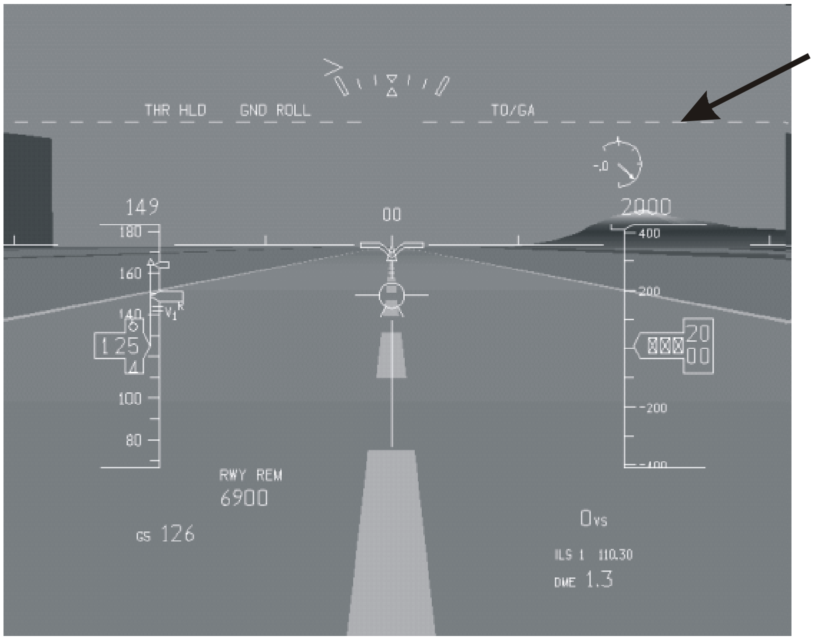
Figure 11 Illustration of Signals Used to Compensate the Acceleration Caret

As with the flight path vector, there was considerable concern as to how this would behave in turbulence. Because of the airspeed and throttle inputs, the caret response is more active in turbulence than the pure inertial solution. However, the pilot can have confidence that the cue is always providing the correct sensing in terms of guidance as to what to do with thrust to maintain airspeed. Testing in the above noted storm at Crescent City, as well as numerous flights in moderate or greater turbulence at Mojave and Victorville indicated that the caret provides very good airspeed control with minimal pilot workload.

5.4 Tailstrike Protection

The margin for tailstrike is critical for stretched commercial transports. As a result, there have been a number of tailstrikes, both on takeoff and on landing. Airline customers have indicated that one such incident can cost more than the amount needed to equip an entire fleet with HUDs. A primary selling point of HUDs to airline management was that it could be used to minimize the potential for tailstrike.

The tailstrike guidance for takeoff was incorporated into the takeoff and go-around (TO/GA) symbology shown in Figure 12. The dashed line across the top of the display is the target pitch attitude for takeoff and initial climb out. At rotation speed, the pilot task is to place the aircraft attitude reference symbol, or boresight, into the gap in the TO/GA line. The TO/GA line is driven by the head-down guidance during climb-out (i.e., it is identical to the head down PFD guidance). However, the initial pitch command is limited to a pitch attitude that will provide sufficient angle-of-attack for liftoff, but with some attitude margin to prevent tailstrike with the landing gear oleos compressed. This attitude is 10 degrees for the 737-800. It is maintained up to a radar altitude of 10 ft., at which time the VGS guidance is smoothly blended to the head-down TO/GA guidance.

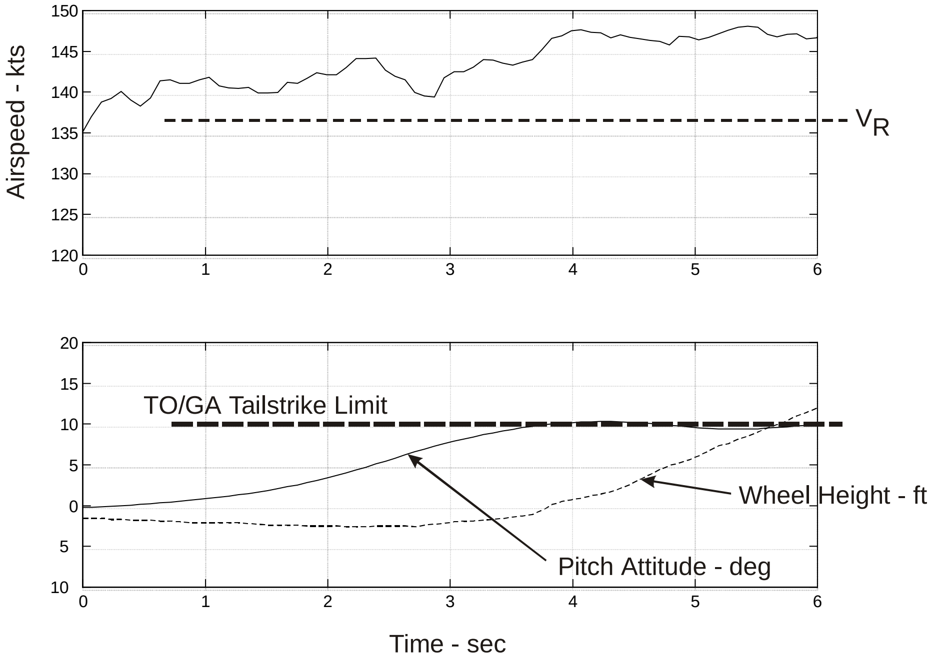


TO/GA Line

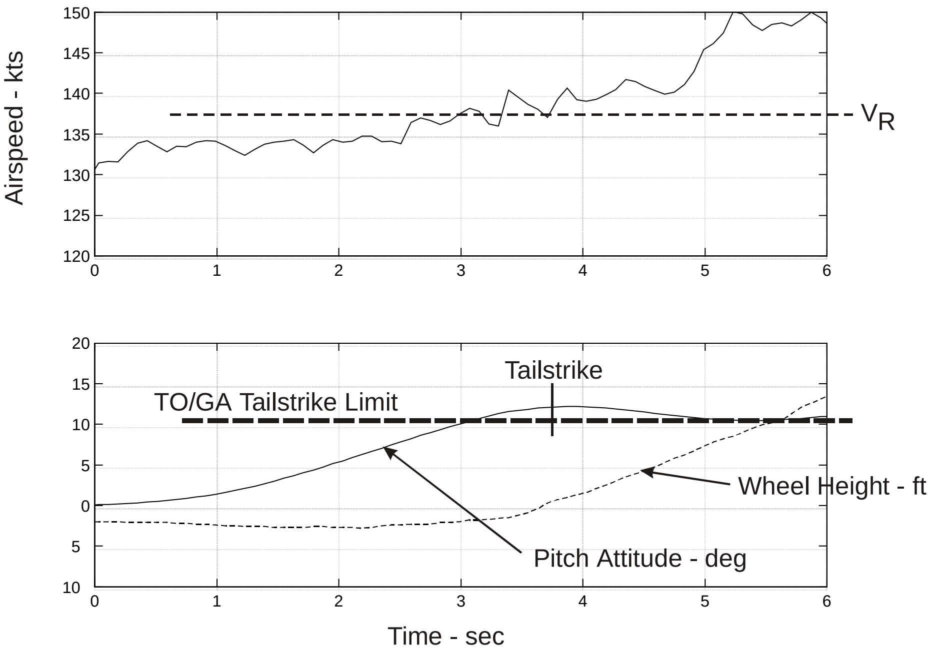
Figure 12 Takeoff Symbology

There was some concern on the part of the FAA that the tailstrike limit on pitch attitude could cause the pilot to achieve less than needed takeoff performance. The counter-argument was that the TO/GA line is advisory, and that the pilot can and will exceed the target attitude if more takeoff performance is necessary. This theory, as well as the accuracy of the tailstrike TO/GA-line limit, was inadvertently flight tested during a takeoff at Victorville, California. The scenario was as follows.

The takeoff was made as the second part of a stop-and-go operation. This was done because touch and go operations were not authorized by the owner of the test aircraft. There was discussion in the cockpit as to the wisdom of initiating a takeoff so far down the runway, but the pilot in command (aircraft owner's captain) insisted that there was plenty of runway (approximately 5000 ft). The winds were strong and gusty, and varying between a crosswind and headwind. During the takeoff roll, a decreasing headwind shear caused the airspeed to stop increasing just below VR. As the end of the runway was rapidly approaching, the HUD evaluation pilot initiated the takeoff rotation at an airspeed slightly below VR. The rotation was quite aggressive, and exceeded the TO/GA line by approximately 2 degrees. Time histories of the takeoff just prior to the tailstrike incident, and of the takeoff with tailstrike incident are shown in Figures 13a and 13b respectively. The pitch rotation in Figure 13a is seen to be initiated at VR and results in an initial attitude of 10 degrees per the TO/GA guidance. In Figure 13b, the airspeed is seen to be holding constant slightly below VR and the rotation is initiated to avoid running off the end of the runway. Here it is seen that the pitch attitude is approximately 12 degrees while the landing gear altitude is below 10 ft. The result was a minor tailstrike, that scraped the tail skid (Figure 14) but did not cause any structural damage.



A) Normal Takeoff - Takeoff Prior to Tailstrike



B) Takeoff With Tailstrike

Figure 13 Takeoff Time Histories – Normal and Tailstrike

Figure 14 Tailskid Following Tailstrike

While certainly not planned, this incident proved that the VGS tailstrike limit is indeed real, and that it is unlikely that a pilot would be compelled to slavishly follow the TO/GA line if there is a risk of going off the end of the runway.

Tailstrike protection for landing is also provided by the VGS. An algorithm was developed to predict the touchdown pitch attitude in the flare for a given pitch attitude and angle-of-attack on the approach. If the predicted touchdown attitude exceeds the tailstrike limit, tailstrike is annunciated on the HUD as shown in Figure 15. Fortunately, we did not flight test this. However, testing in the simulator has shown that the algorithm reliably predicts tailstrike without giving false alarms.

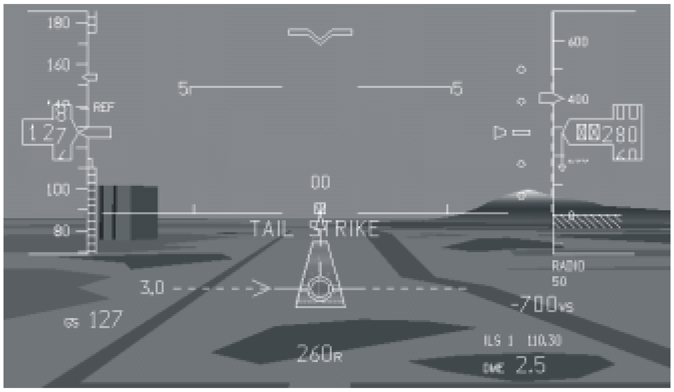


Figure 15 Tailstrike is Predicted at Touchdown

5.5 Flare Guidance

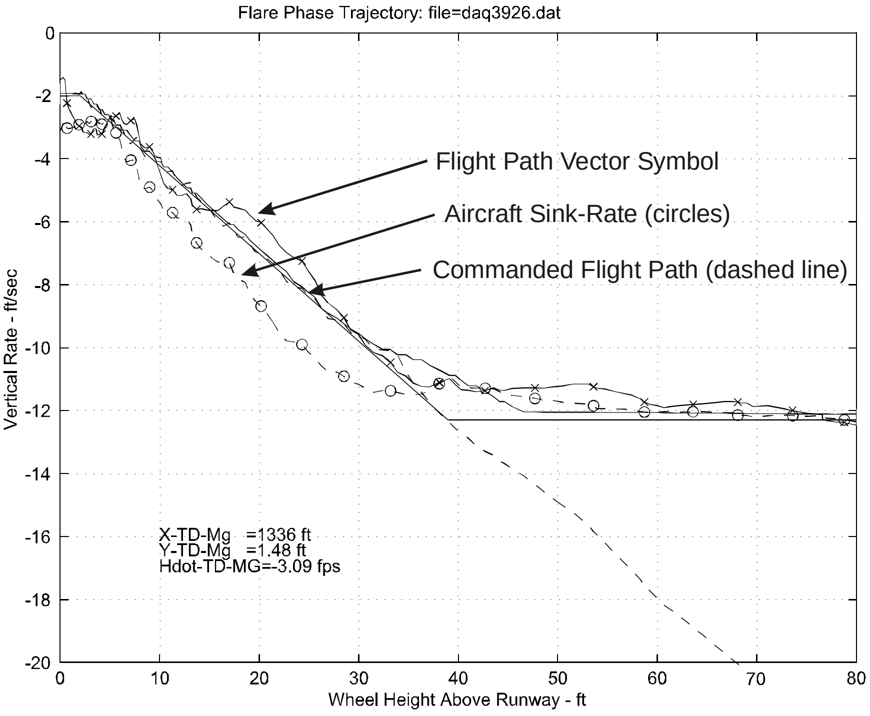
With quickening in FPV and pursuit guidance, the flare guidance is very straightforward. This guidance simply commands a decreasing flight path angle as a linear function of altitude resulting in an exponential flare. The guidance cue is very predictable, and always winds up in the same place relative to the horizon. The pilot task is to keep the FPV symbol centered over the guidance cue. Since the dynamics of the FPV are the same as pitch attitude, it is essentially a pitch-tracking task. The flare guidance cue was initially optimized in the Boeing M-Cab simulator. However, once flight-testing was initiated, it was found that the parameters obtained from the simulator were not optimum for flight. The flare parameters were reset in flight test. Establishing and validating the flare guidance was accomplished through numerous landings under all possible wind conditions and runway elevation and slope.

Interestingly, the flare cue was very easy to track in flight, but resulted in moderate workload in the simulator. This was a problem because the certification process is primarily done via 1000-plus simulator landings. (The stated purpose of the FAA flight tests is to verify the simulator results). It was decided not to compromise the aircraft simply to pass the certification process. In the end, some of the Monte Carlo subject pilots did notice that the flare cue was more difficult to track in the simulator than they would like, but acceptable. The touchdown footprint was inside the FAA requirements (Reference 1) by a large margin, so it all worked out in the end. The lesson learned was that the flare guidance must be set via flight-testing. All of the FAA evaluation pilots, as well as the end-user airline pilots, agreed that the flare cue was easy to track in the aircraft.

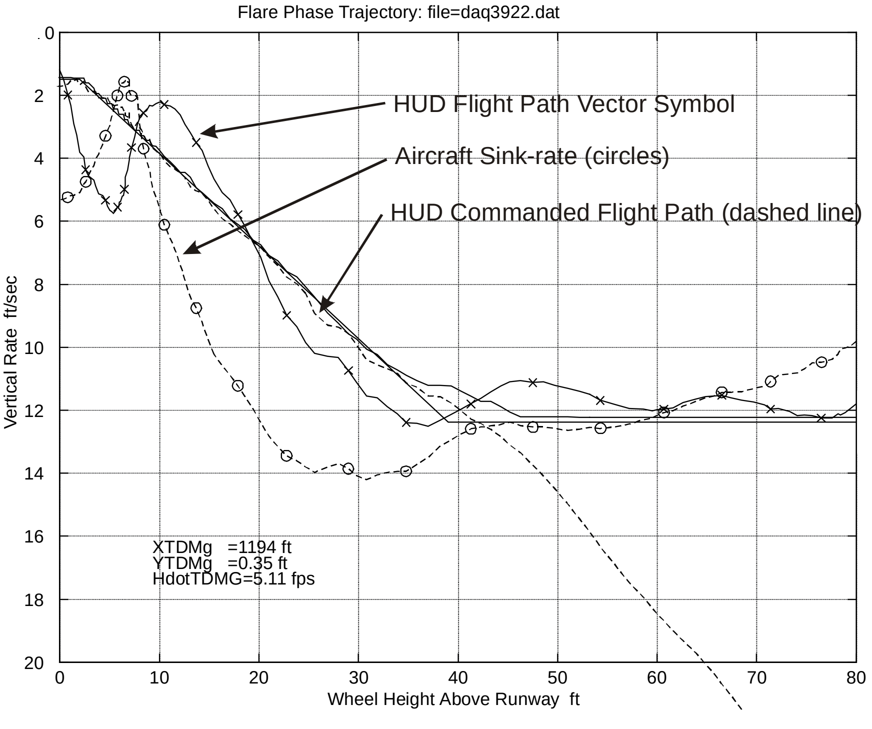
5.6 HUD and Autoland

The HUD and autoland guidance algorithms are completely independent. This makes the HUD a natural monitor for the autoland. In order to check that the HUD guidance cue is a reasonably accurate measure of the autoland flare, landings were made with the autoland engaged under a variety of runway and environmental conditions. In most cases, the HUD guidance cue was centered during the autoland flare. This is not surprising because the objective of both control laws is an exponential flare.

A few exceptions were encountered during flight-testing. These invariably occurred during difficult conditions, with gusty winds and windshear. The most dramatic example was at Spokane. Runway 21 at Spokane has a large and variable slope in the touchdown zone, the terrain in front of the runway has a large berm (tends to confuse the radar altimeter), and the winds on the day of this event were gusty with significant directional windshear near touchdown. The HUD landings were well within the acceptable range, but pilot workload was moderate due to the gusty wind and windshear. Figure 15a shows a phase plane plot of one of those HUD landings. Because of the difficult conditions, it was decided to investigate the ability of the HUD to monitor an autoland landing. Figure 15b shows that the autoland became destabilized at the bottom of the flare and touched down hard at 5.1 ft/sec. The oscillatory FPV response on the VGS ft clearly indicates a problem. This data indicates that a go-around should be initiated if the VGS is used as a monitor for the autoland, and the FPV response becomes oscillatory.



A) HUD Landing - Runway 21 at Spokane



B Autoland Landing - Runway 21 at Spokane

Figure 15 Flare Phase Trajectories – Spokane

6 LESSONS LEARNED

A number of lessons were learned during this flight test program.

Close coordination with the end-user pilots is essential and is felt to be responsible for good pilot acceptance. Reports from the airline users indicate that the HUD is used for a high percentage of takeoffs and landings on the line. Some senior pilots have switched to the 737-800 just to fly the HUD.

Use of a PC simulator program as a symbology development tool, and for coordination with end-user pilots was extremely valuable. This program, with minor modifications, also provided an excellent training aid.

Leave the landing gear down for multiple landings such as required for HUD flare law development – check brake temperatures – touch-and-go landings result in less wear and tear.

Flight-test HUD symbology in turbulence – it is the worst-case scenario. Do not believe simulator results related to pilot workload for HUD tracking in turbulence.

If the HUD is used as an autoland monitor, and the FPV indicates a destabilized flare – go around.

Don't believe any simulator ground-effects model – optimize the HUD flare laws in flight test.

7 REFERENCES

1. Anon., Criteria for Approval of Category III Weather Minima for Takeoff, Landing, and Rollout, FAA AC 120-28D, July 1999.