Landing an H-60 Helicopter in Brownout Conditions Using 3D-LZ Displays

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This paper details the results of the flight test of the Three Dimensional Landing Zone (3D-LZ) LADAR and the Brown-Out Symbology System (BOSS). The LADAR was built by H.N. Burns Engineering Corp. under a contract from the U.S. Air Force Research Laboratory (AFRL). The BOSS symbol set was originally developed by the U.S. Army Aeroflightdynamics Directorate (AFDD), and upgraded by AFRL. These two technologies were integrated together on the AFDD EH-60L aircraft to enable pilots to safely fly the aircraft (with symbology) while viewing obstacle locations (from the LADAR) throughout landing and hover in severe brownout conditions. Four pilots were able to safely land the aircraft in heavy dust 23 times out of 31 attempts at the dust course at Yuma Proving Ground. Two pilots also conducted an approach-to-high-hover, hover translation, and hover over a load maneuver (without sling cables) in the dust. Pilot performance data as well as subjective rating data are presented in this paper.

Introduction

The purpose of this test was to evaluate a sensor and display system, designed to enable safe brownout landing, go-around, and hover maneuvers. The test was conducted using the EH-60L helicopter, in a representative heavy dust environment at the Yuma Proving Ground (YPG) dust course near obstacles such as wires and poles. This paper describes the symbology and pilot performance in detail. Companion papers describe the sensor and flight test operations (Refs. 1-2).

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The Three Dimensional Landing Zone (3D-LZ) system had two major components. One component was the Three Dimensional Landing Zone (3D-LZ) Laser Detection and Ranging (LADAR) subsystem which mapped the landing site. This LADAR was developed by the H.N. Burns Engineering Corporation under a contract with the Air Force Research Laboratory (AFRL). The LADAR subsystem created a persistent and geo-referenced 3D database of the terrain and obstacles. The subsystem then generated ego-centric and exo-centric views of the terrain and obstacles for the pilot's displays. The other major component tested was the Brown-Out Symbology System (BOSS), developed by the US Army Aeroflightdynamics Directorate (AFDD), and improved upon by AFRL. This display symbology subsystem provided aircraft state and landing point position through two-dimensional graphics and text. The two subsystems were integrated together by overlaying the symbology on top of the LADAR imagery on the pilot's displays. System development costs, flight test costs, engineering and pilot support were shared between the U.S. Air Force, Army, Navy, and Marine Corps. AFRL was the overall program lead.

Background

This background section details the two independent paths which ultimately led to the integrated 3D-LZ LADAR and BOSS display. The sensor development path is presented first, followed by the symbology development path. A simulation where the two development paths came together is then detailed.

History of Sensor Development

AFRL Brownout Study. Due to safety hazards resulting directly from brownout conditions during landing, the Air Force Special Operations Command (AFSOC) wrote a letter in November 2005 asking for AFRL's assistance in developing and fielding a solution. In response, AFRL conducted a five month study to develop and document a clear understanding of the user needs and desired capabilities, gather system requirements from the user, discuss possible integration issues, explore a wide variety of solution and technology options, and then create an integrated development roadmap. Seven teams were assembled: 1) systems engineering 2) operations 3) technology transition 4) dust characterization and abatement 5) sensors 6) aerodynamics and flight control 7) human effectiveness. The teams collectively generated a large solution possibility set. A systems engineering approach was used to select the optimal solution configuration and provide systematic flow-down from requirements to the solution formulation.

The systems engineering team was comprised of operational pilots completing their systems engineering Master's degrees at the Air Force Institute of Technology (AFIT). This team defined the set of core operational tasks necessary in rotary-wing aircraft landings, provided systems requirements, and developed a structured solution analysis based on these requirements. Requirements were segregated into functional (e.g. range, display effectiveness, etc.) and non-functional (cost, size, weight, etc.) and were given objective measurable values and a defined limit where the level of performance fails to produce added value to the user. By analyzing past brownout related mishaps, the team was able to prioritize the system objectives into a hierarchy. Comparison of the possible solution set developed by the collection of the seven AFRL teams was completed using this weighted hierarchy together with the operational task requirements, measurable performance requirements, applicable standards, and utility functions.

The solution set was reduced to those technologies holding the most promise for transition to the rotary-wing aircraft fleet. Hence, fundamental changes to the aerodynamics and dust abatement solution ideas were excluded from the analysis. The remaining technologies were categorized into external sensors, human interface, and flight control capabilities. Sensor options included sparse array non-imaging radar, imaging millimeter wave radar, LADAR, and combinations of these sensors. Human interface technologies included a helmet mounted display (HMD) with symbology, a head tracked HMD with video and symbology, 3D audio cueing, tactile cueing, and combinations of these visual and non-visual displays. Finally, flight control options included improved aircraft handling qualities, a coupled approach with enhanced obstacle avoidance, and the combination of the previous two options. "No upgrade" was also an option in each category. Since all combinations of the technologies resulted in 192 possibilities, the systems engineering team first selected the 32 configurations with the highest probability of generating improved capability to the operator for further evaluation.

Each of the 32 system configurations were compared against the quantitative requirements with known or estimated values. Qualitative comparisons such as "display effectiveness" were rated with a rule-based subjective rating ranging from 0 (no upgrade) to 10. The ratings were then weighted and combined to provide an overall score for each of the 32 selected configurations in terms of the improvement to the baseline aircraft. The analysis provided recommendations for configurations based on the level of desired performance (Refs. 3-4). For a high performance system, the recommendation was for sparse array radar combined with a LADAR sensor to provide a 3D world model of the landing site. The top recommendation was to provide this sensor data to the pilot via a head-tracked, helmet mounted display with symbology and/or synthetic vision.

Other Efforts. Parallel to the AFRL study, DARPA issued the "Sandblaster" contract to develop a brownout landing solution. The solution included an automated fly-by-wire approach (Sikorsky), a radar (Sierra Nevada), a synthetic vision display (Honeywell), and symbology (Sikorsky). This system was flight tested in 2009 at AFDD (Ref. 5). The radar was derived from a system developed for the US. Army Aviation Applied Technology Directorate (AATD) (Ref 5).

LADAR Development. For the LADAR sensor, AFRL selected the H.N. Burns Engineering Corporation. This company produces a commercial airborne LADAR used in the surveying industry, called the Eye-safe Burns engineering Active Infra-Red (EBAIR) sensor (Fig. 1). The EBAIR surveying LADAR is an azimuth line-scanned system; the image shown in Fig. 2 required a fly-over of the ground to be scanned. A very high resolution 3D database was created from the LADAR samples including poles and wires as shown in Fig. 2. The EBAIR system did not have a real-time graphics processor needed to render the digital terrain for the pilot. The image shown in Fig. 2 was post-flight processed, and then rendered from a ground-level eye-point.

Fig. 1. EBAIR LADAR tested on a UH-1.

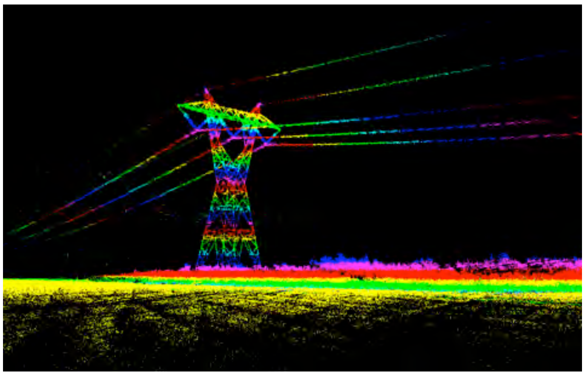


Fig. 2. Post-processed 3D image from EBAIR.

The EBAIR was modified with a vertical scanning mirror so that 3D imagery could be collected from a stationary position. This system was called the Scanned Experimental EBAIR (SEEBAIR) shown in Fig. 3. Critical to the military, the SEEBAIR was able to scan the intended landing zone from a helicopter without the need to first over fly the landing zone. A sample image taken from a hover is shown in Fig. 4. The SEEBAIR was used earlier to collect ground-based data in dust conditions at YPG in 2007. The field test data from the SEEBAIR ground tests showed that it might be possible to differentiate laser reflections from dust and hard targets.

With funding from the Defense Rapid Reaction Technology Office of the Office of the Secretary of Defense, a dust preprocessor filter was developed by H.N. Burns Engineering Corporation which could discriminate between dust returns and solid surface returns for each sample. This filter mitigated the corruption of the 3D database from dust returns, while preserving returns from solid surfaces. The dust preprocessor filter was installed into the SEEBAIR and tested successfully at Yuma Proving Ground in 2008.

Fig. 3. SEEBAIR LADAR.

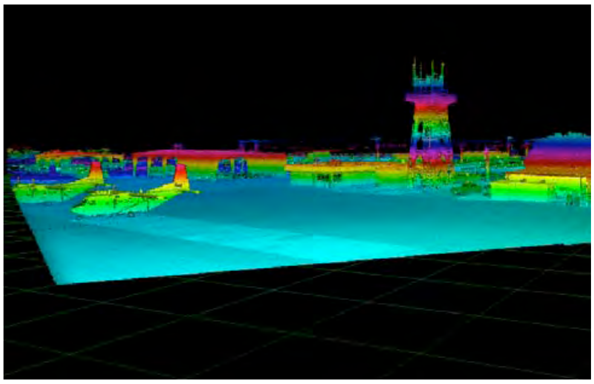


Fig. 4. Post-processed 3D image from SEEBAIR.

The success of the SEEBAIR sensor lead to the start of a contract between H.N. Burns Engineering Corporation and the Munitions Directorate of AFRL, located at Eglin Air Force Base, FL. A new LADAR was developed, based on the SEEBAIR with a dust preprocessor, but with added gimbals replacing the vertical scanning mirror. The new (sub)system was called the 3D-LZ. In addition to the LADAR sensor, the 3D-LZ system development included a high performance inertial navigation system (INS), a multiprocessor computer and a graphics generator. The multiprocessor computer generated geo-referenced 3D point clouds from the raw LADAR data using the real time inertial solution from the INS. The graphics generator rendered forward-looking and downward-looking terrain and obstacle images in real time from the stored geo-referenced point cloud data. The dust preprocessor allowed the collection of a high definition 3D image of the landing zone before brownout occurred, while automatically rejecting returns from dust.

History of Symbology Development

AH-64A. The plan-view hover symbols in the BOSS symbology have roots in the AH-64A HMD, shown in Fig. 5 (Ref. 6). The aircraft reference symbol in the center of the screen is the plan-view own-ship location. The desired hover point is shown as an octagon shaped symbol. On the AH-64A, this point was the aircraft's previous location marked by the pilot, typically in a hover. The velocity vector shows the plan-view direction and magnitude of horizontal velocities, with forward velocities shown in the direction of the top of the screen. The acceleration cue symbol is used as a predictor for the velocity vector, and includes both horizontal acceleration terms and quickening terms (Ref. 7). These four symbols allow the pilot to come to a hover over a defined hover point. The pilot manipulates the cyclic stick to track the hover location symbol (target) with the acceleration cue symbol (controlled element). The velocity vector lags behind the acceleration cue. This tracking strategy results in the pilot commanding smaller velocities the closer the aircraft is to the hover point.

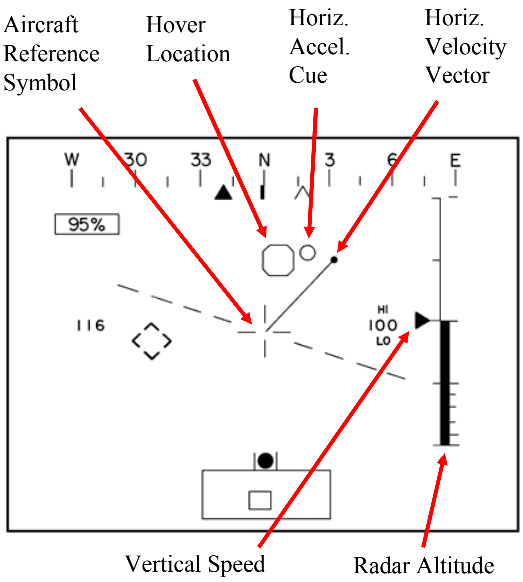


Fig. 5. AH-64A bob-up page.

To come to a hover without regard to location, the pilot places the acceleration cue symbol in the center of the aircraft reference symbol. The velocity vector will again follow after some delay. As long as the acceleration cue symbol is kept on the aircraft reference symbol (which requires continuous cyclic input), the aircraft will eventually come to a hover.

The AH-64 radar altimeter is a tape, with zero at the bottom, and 200 ft on top. Note that the tape is less visually compelling (fewer pixels displayed, and further from the screen center) the closer the aircraft is to the ground.

NASA VSRA. NASA Ames Research Center developed a new variable stability flight control system and Head Up Display (HUD) for a research AV-8B Harrier aircraft (Fig. 6, Refs. 8-11). The aircraft was called the V/STOL Systems Research Aircraft (VSRA). The HUD had two pages. The central portion of the hover page is shown in Fig. 7.

Fig. 6. NASA Ames AV-8B.

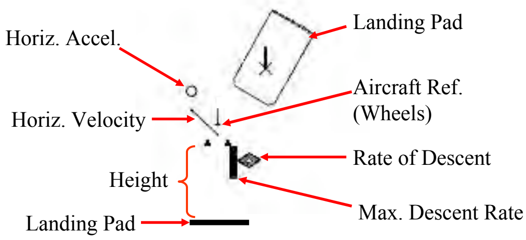


Fig. 7. Center portion of the NASA Ames VSRA HUD.

The plan-view symbols are similar to the AH-64A hover symbols, though the task changed from simply hovering to making an approach to hover. Different than the AH-64A display is the symbol indicating the height above the landing pad as shown in Fig. 7. This symbol moved up the screen as the aircraft descended, thereby becoming more visually compelling. Note also the vertical speed indicator is in-line vertically with the rising deck symbol. These two symbols were drawn using different icons, but otherwise they behaved the same as the newer BOSS symbology.

Univ. of Iowa. All the main elements of what would later become the BOSS symbology were first implemented in a simulation at the Univ. of Iowa Operator Performance Laboratory in 2006 (Fig. 8, Ref. 12). This simulation was funded by AFDD, the U.S. Army Utility Helicopter Project Management Office, and Rockwell-Collins. This display, shown in Fig. 9, has the plan-view hover symbols from the AH-64, the rising ground symbol from the VSRA, and the plan-view heading indicator from the Common Avionics

Architecture System (CAAS) display (Ref. 13) implemented on the CH-47F and numerous Army special operations aircraft.

New at the time, on the Univ. of Iowa display, was the vertical speed indicator drawn as a tape and intentionally overlapping the rising ground symbol, which has advantages detailed later in this paper. Also new was a plan-view horizontal target speed symbol, to guide the pilot from high speed to hover, near the landing point. This symbol is the half-circle icon in Fig. 9, and it is the target location on the screen for the acceleration cue and velocity vector. The target speed symbol was constrained to the aircraft's longitudinal axis for this simulation.

Fig. 8. Dome simulator at the Univ. of Iowa 2006.

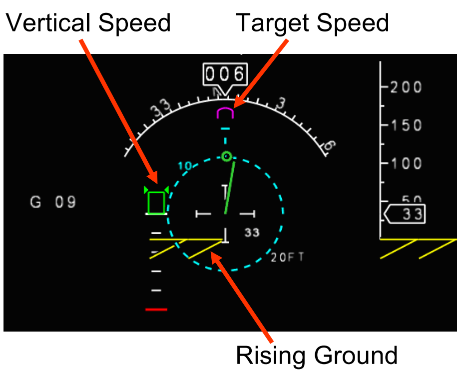


Fig. 9. Hover display tested at the Univ. of Iowa.

NASA VMS. The Aeroflightdynamics Directorate and NASA-Ames Research Center conducted a simulation on the Vertical Motion Simulator (VMS) in 2007 (Fig. 10, Ref. 14). Both panel-mounted and Night Vision Goggles Head Up Display (NVG-HUD) displays were tested with BOSS symbology (Fig. 11) and the AVS-7 NVG-HUD as a base-line (Ref. 15).

Fig. 10. NVG-HUD and panel mounted displays used in the NASA Vertical Motion Simulator 2007.

Fig. 11. Hover page of BOSS NVG-HUD.

Instead of a half circle icon for target speed, the pentagon shaped icon showed target speed when drawn with solid lines, and showed target position when drawn with dashed lines. Overall, the symbology set compared well against the AVS-7 set, particularly in vertical speed. However, pilots had negative comments regarding the pentagon symbol suddenly changing position on the screen when it changed from indicating target speed to indicating target position.

NRC. In 2008, two variants of the BOSS symbology set were implemented on the Bell 412, operated by the National Research Council Canada (NRC) shown in Fig. 12. One BOSS set was the same as that flown in the VMS simulation. The other set is shown in Fig. 13. Here, the target speed symbol was once again drawn as a half-circle, as it was at the Univ. of Iowa, but in this implementation the icon would rotate about the own-ship symbol and thus provide a target ground-track to the landing point. Other changes were also tried and rejected by the pilots (Ref. 16).

Fig. 12. BOSS symbology was first flight tested on the National Research Council Canada Bell 412 in 2008.

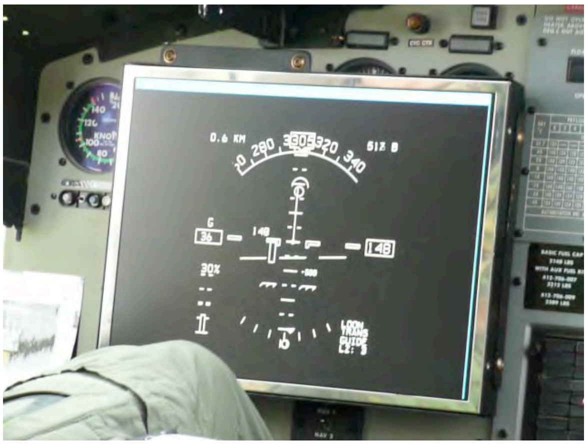


Fig. 13. One of the BOSS variants tested at NRC.

AFDD SV Simulator. After the flight test at NRC, the BOSS symbology was selected as one of two candidate symbol sets for the 3D-LZ program. The HH-60 Block Change Order BCO005 symbology was selected as the other set. The BOSS symbology set was redesigned to incorporate lessons learned from previous tests, and to implement scale changes on the Horizontal Situation Display to integrate with the 3D-LZ LADAR. In particular, four scales were implemented for the landing point position symbol and the background downward-view LADAR imagery. The 2000 ft scale was set to match the maximum range of LADAR, and this was the distance represented from the own-ship symbol to the top of the screen. The 1000 ft, 500 ft, and 250 ft scales were added to show finer details of the terrain and obstacles as the aircraft approached the landing point. A method was implemented by which the pilot could move the target landing point symbol during the approach, using a two-axis switch on the collective.

The 3D-LZ version of the BOSS symbology was implemented in the Synthetic Vision (SV) simulation cab at AFDD in early 2009 (Fig. 14, Ref. 17). The LADAR simulation was not yet available, so the systems were not yet integrated. Results from this simulation showed that changing scales on the Horizontal Situation Display (HSD) were not desirable, but it was otherwise flyable with one exception. That exception was that for the direct landing maneuver, the approach-to-landing task was difficult to complete with desired performance if the landing point was moved while on the 250 ft scale; the aircraft was too close to the landing point to make changes. Another maneuver was also tested, which was an approach to 50 ft hover, reposition, and descent. This maneuver was rated as easier than the direct approach to landing. The helicopter model was the Enhanced Stability Derivative (ESD) model, commented as easier to fly than an actual aircraft by the pilots (Ref. 18).

Fig. 14. AFDD synthetic vision cab.

Integrated Simulation of BOSS and 3D-LZ LADAR

After the AFDD simulation with the 3D-LZ version of BOSS, a higher fidelity simulation was conducted in the Synthetic Immersive Research Environment (SIRE) facility at AFRL (Fig. 15). A LADAR simulation was added, which used pre-sampled LADAR data from the Yuma test site. A large dome projection system (160^o horizontal x 80^o vertical FOV) was used, with improved brownout visualization, and a high resolution terrain database that modeled three landing sites located at Yuma Proving Grounds, AZ. The helicopter model was upgraded to the high fidelity GENHEL model (Ref. 19).

The experiment utilized a 2x2x2 within-subjects, repeated measures full factorial design. One factor was sensor type: LADAR and Forward-Looking Infrared (FLIR). Another factor was symbology type: HH-60G Block Change Order 5 and BOSS. A Third factor was approach type: direct and offset (where the landing point needed to be moved). Eleven pilots completed the simulation. All evaluators were US military trained helicopter pilots. The distance error at touchdown was significantly lower with the LADAR sensor (25 ft) when compared to the FLIR (68 ft) ($p<0.001$), and was lower for the direct landing maneuver (27 ft) when compared to the offset maneuver (65 ft) ($p<0.001$). Comparing symbol sets, the only statistically significant difference in the objective data was that the forward speed was less for the BOSS display (0.9 knots) as compared to the HH-60 display (1.7 knots). There were larger differences in the subjective data.

Fig. 15. AFRL SIRE helicopter simulator.

The average Handling Quality Rating (HQR) was 4 for BOSS vs. 5 for the HH-60 symbology set, where lower was better (Fig. 16, Ref. 20). Definitions of the HQR values are provided in Appendix A).

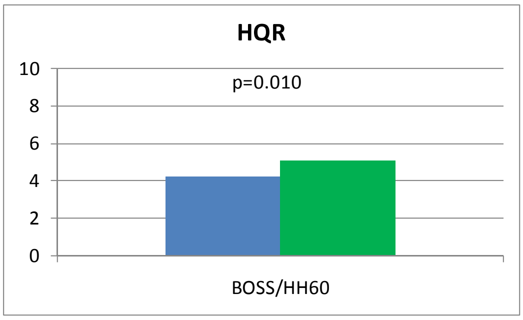


Fig. 16. Average Handling Quality Rating.

The Visual Cue Ratings (VCRs) were also lower (better) for the BOSS symbology as shown in figs. 17-18 (Ref. 21 and Appendix A). When asked to rank the test configurations from easiest to most difficult, the BOSS symbology with the LADAR imagery in the background during the direct approach was selected as the easiest while the HH-60 symbology with the FLIR imagery with the offset approach was selected as most difficult (Fig. 19).

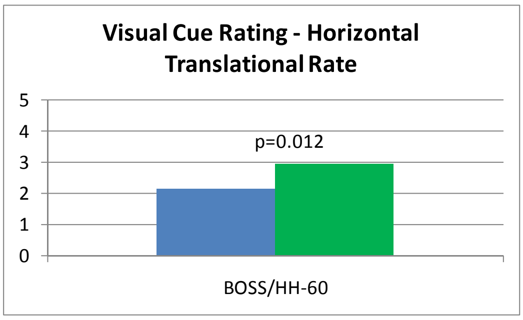


Fig. 17. Average Horizontal Translation Rate Rating.

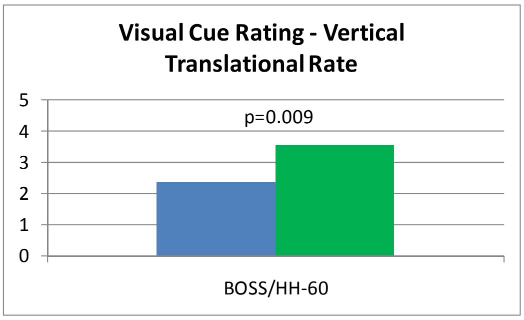


Fig. 18. Average Vertical Translation Rate Rating.

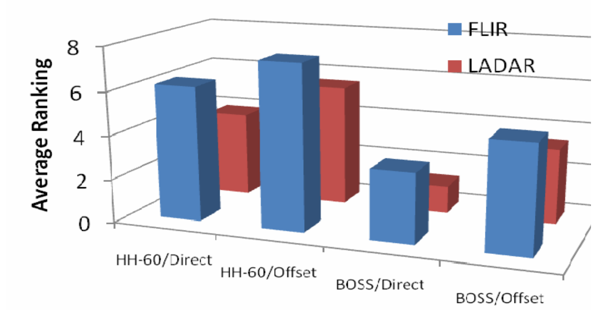


Fig. 19. Average Preference Ranking

There were six major outcomes of the simulation:

1) The decision was made that only the BOSS symbology would be used in the flight test.

2.) The LADAR display was recommended for the flight test, as implemented in the simulation.

3.) The offset landing was dropped from the proposed flight test.

4) Pilots requested a single display, and AFRL developed the "switched" display, which switched between a Vertical Situation Display (VSD) and a HSD at 30 knots.

5) The horizontal speed guidance algorithm, which was a linear speed vs. distance relationship, was debriefed as too slow. AFRL altered the algorithm to have two sections; pilots started with a constant deceleration which later blended into the linear speed vs. distance algorithm at 1000 ft distance from the landing point.

6) AFRL responded to pilot comments indicating that they wanted to follow a target vertical speed symbol to control descent angle rather than follow the flight path marker symbol (detailed later in this paper). This symbol was not implemented on previous versions of BOSS symbology because it required knowledge of the height of the landing point with respect to the aircraft. Since the LADAR could measure this height, AFRL added a new target vertical speed symbol and associated vertical speed guidance algorithm to the 3D-LZ version of the BOSS symbology.

Method

The aircraft modifications and test methods for the 3D-LZ flight test at YPG are described in detail in Ref. 1. The LADAR is described in detail in Ref. 2. This section provides only a brief overview of the aircraft modifications and the LADAR, and instead focuses on the symbology implementation for the flight test at YPG.

Equipment Description

The US Army EH-60L Black Hawk aircraft Serial Number 87-24657 was modified to install the H.N. Burns Engineering 3D-LZ LADAR as shown in Fig. 20. The LADAR was set to a 2,000 ft range, though it was capable of greater range. The LADAR's dust rejection filter determined whether each sample was dust or a hard surface. This filter had nearly 100% accuracy in rejecting dust returns. The LADAR operated continuously throughout the dust landing and hover maneuvers; it did not need to be turned off to prevent contamination of the database from dust returns.

A Max-Viz EVS-1500 FLIR camera and a color camera were installed on fixed mounts, with the center of each field-of-view aligned with the aircraft centerline. All three imaging sensors could provide background imagery on the evaluation pilot's displays with symbology overlaid. The forward-view LADAR image was set to 60 degree vertical x 45 degree horizontal Field-of-View (FOV). The color nose camera had the same FOV. The FLIR had a 53 x 40 degree FOV.

Fig. 20. Gimbaled LADAR, fixed FLIR, and fixed color camera mounted on aircraft nose.

Two 6x8 inch, color, sunlight-readable, LCDs were installed in the right cockpit for the evaluation pilot as shown in Fig. 21. The displays were mounted in portrait orientation, and they had a resolution of 1024x768 pixels each.

Fig. 21. LCDs were mounted on right side of the instrument panel.

In the left cockpit, a sunlight-readable Rockwell-Collins EyeHUD was installed as shown in Fig. 22. This display allowed the safety pilot to look out the window while he also monitored the symbology. No background terrain image was displayed on the EyeHUD. The velocity vector, acceleration cue, and target landing point did not scale on the safety pilot's display, and were set to 400 ft and 40 knots from the display-centered own-ship symbol to the top of the screen.

Fig. 22. Rockwell-Collins EyeHUD display.

Key elements of the hover symbology were the velocity vector and acceleration cue symbols detailed in Fig. 23. Unlike the AH-64A/D display, the acceleration cue symbol on the test aircraft did not have quickening or prediction terms; it was driven only by horizontal acceleration. Figure 24 shows the target speed symbol and target position symbol. The target speed symbol is scaled the same as the velocity vector. At 0.8 nm the target speed symbol turned on. The target speed algorithm always started at the speed the aircraft was at when it crossed the 0.8nm distance boundary. As the aircraft approached the landing point the horizontal speed guidance algorithm directed the pilot to slower speeds. In addition to providing the desired speed, the target speed symbol also rotated about the own-ship symbol to provide target ground track to the landing point. Once the pilot was close to the landing point, the target landing point position symbol would overtake the target speed symbol, and the pilot would switch from tracking target speed to tracking target position. The speed guidance symbol turned off at 5 knots; typically the pilot was tracking the target position symbol at that time.

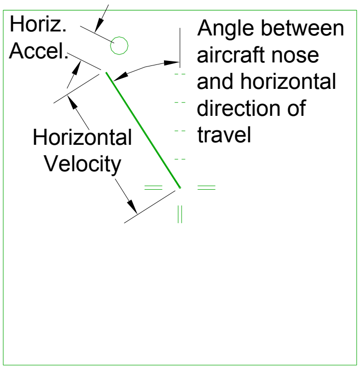


Fig. 23. Plan view velocity vector and acceleration cue.

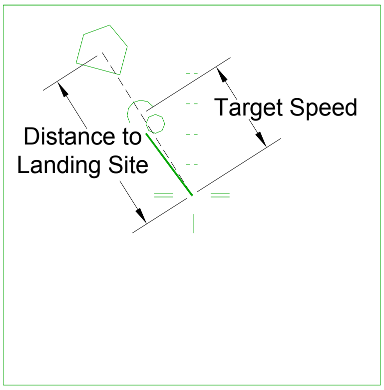


Fig. 24. Target speed and position symbols.

The speed guidance equations used in earlier simulation tests (Refs. 14, 17) were determined to be too slow during the AFRL simulations. The linear speed vs. distance equations were modified by AFRL to add a constant deceleration portion for most of the distance as shown in Fig. 25. At 1000 ft, the constant deceleration equations transitioned to a linear speed vs. distance guidance algorithm. The reason for keeping the linear speed vs. distance portion was that it decreased the deceleration near the landing point, as compared to the constant deceleration algorithm. Therefore, there was a smaller attitude change required near the landing point, close to the ground.

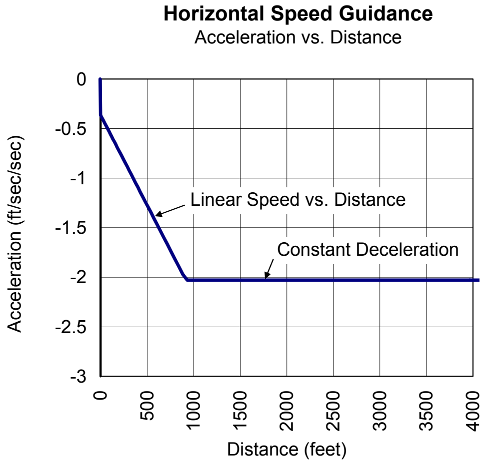


Fig. 25. Longitudinal accelerations for the horizontal speed guidance algorithm.

Figure 26 shows the commanded ground speed as a function of distance for the horizontal speed guidance algorithm. As can be seen, the transition between algorithms was smooth.

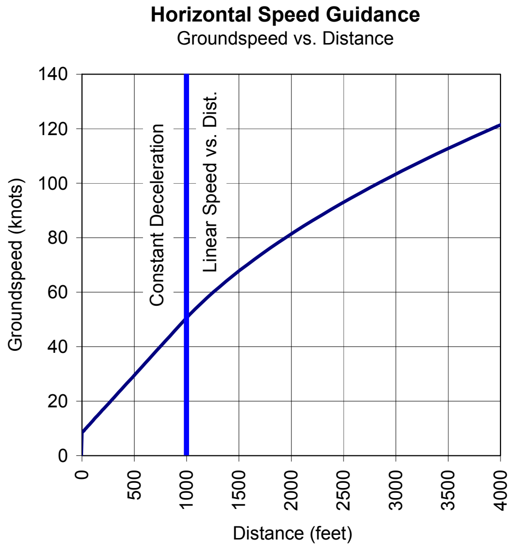


Fig. 26. Commanded speed for the horizontal speed guidance algorithm.

There was a scale associated with the velocity vector, acceleration cue symbol, target speed symbol, and target position symbol. The scales for those four symbols changed simultaneously in factors of two. Figure 27 shows the scales for the velocity vector, target speed, and the target landing position symbol. Although the scale on the acceleration cue symbol also changed in factors of two, that scale was not shown on the display. Each increase in scale sensitivity appeared to the pilot as an increase in sensitivity of the control inputs.

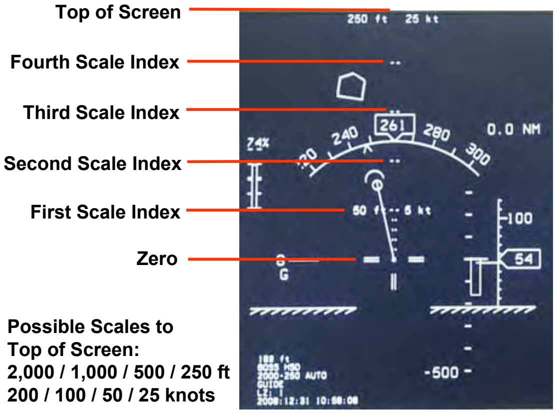


Fig. 27. Scales for the horizontal velocity, target velocity, and target position symbols.

Figure 28 shows the integrated radar altimeter and vertical speed indicator used for the approach to high hover maneuver. The approach-to-high hover maneuvers were started visually (using out-the-window view) and the pilots transitioned to the panel mounted displays at a time of their choosing. Once the target altitude symbol reached the end of the vertical speed tape, the pilots would track the target altitude symbol with the end of the vertical speed tape using collective inputs. Performing this tracking task allowed the pilots to asymptotically reach the target altitude. Although a descent from high hover maneuver was not flown in this test, the capability exists with this symbology to track the bottom of the rising ground symbol with the vertical speed tape, and smoothly transition from high vertical speeds at high altitudes to low vertical speeds at low altitudes. The altimeter and vertical speed symbols are called "integrated" because the moving element of one indicator (end of the vertical speed tape) is controlled by the pilot to be positioned next to the moving element of the other indicator (target radar altitude) to achieve the desired descent profile.

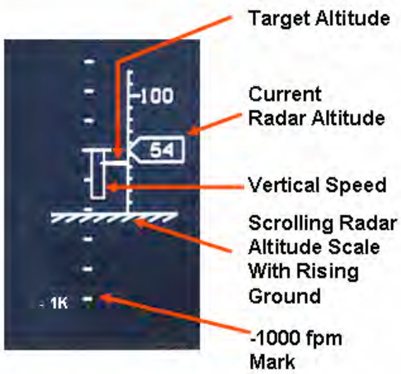


Fig. 28. Combined altimeter and vertical speed indicator with target altitude symbol used for the approach to high hover maneuver.

Figure 29 shows the altimeter and vertical speed indicator used for the landing maneuver. In this case, the target altitude symbol was replaced with the target vertical speed symbol. To stay on the vertical guidance profile, the pilot manipulated the collective control to place the end of the vertical speed tape inside the target altitude symbol. The vertical speed guidance symbol guided the pilot on a specific profile shown in Figs. 30-31. The vertical profile started as a constant descent. At 1,000 ft range from the landing point, the algorithm transitioned to target altitude (in feet) being twice the ground speed (in knots). The vertical speed guidance symbol also turned off below a horizontal ground speed of 5 knots.

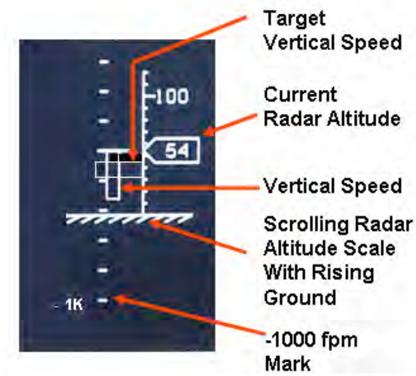


Fig. 29. Combined altimeter and vertical speed indicator with target vertical speed symbol used for the landing maneuver.

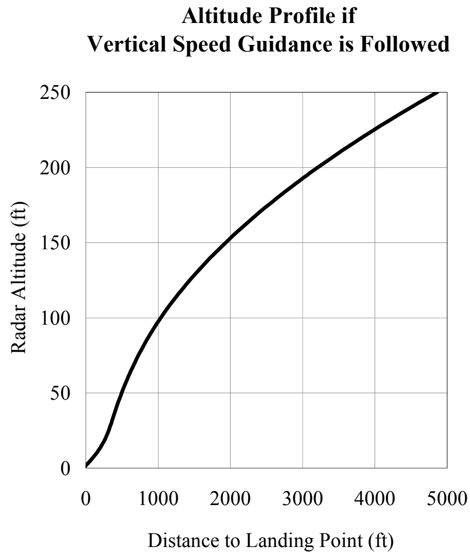


Fig. 30. Vertical profile for the vertical speed guidance algorithm.

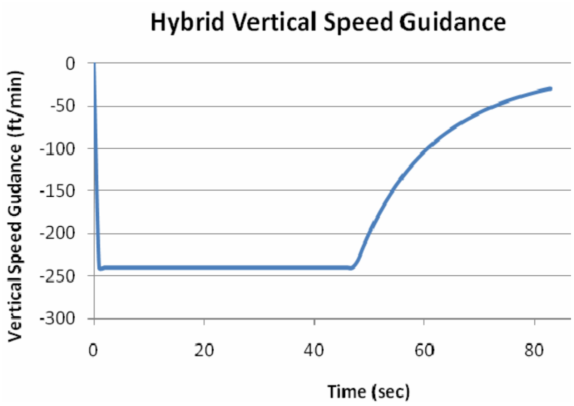


Fig. 31. Vertical speed guidance as a function of time.

Figure 32 shows the flight path marker symbol, which represents the forward-view direction of travel with respect to the terrain imagery. The four evaluation pilots reported that they used the vertical speed guidance symbol (Fig. 29) instead of the flight path marker symbol for control of the descent angle. They also reported that they used the plan-view horizontal speed guidance symbol (Fig. 24) instead of the speed guidance symbols on the left wing of the flight path maker. The flight path marker symbol was visible on all displays with forward-view terrain imagery. Although not the case for this test, the flight path marker symbol is useful in situations where the elevation of the landing point is not known ahead of time, nor can be measured with a sensor. The flight path marker was set to turn dashed below 30 knots ground speed, and to turn off below 20 knots ground speed.

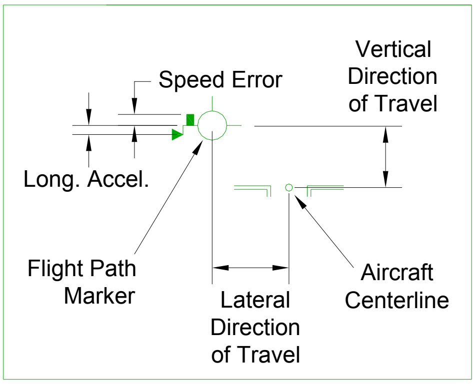


Fig. 32. Flight path marker symbol.

The BOSS symbol set is detailed in Fig. 33. Three different variants of the BOSS display were tested, along with three different types of terrain imagery. The LADAR terrain image types are shown in Fig. 34, while the FLIR terrain image is shown in Fig. 38. The true color LADAR image was only used beyond ¼ nautical mile from the landing point. The detailed discussion of obstacle detection with the different LADAR and FLIR images is provided in the companion paper (Ref. 1).

One of the three symbol sets is called "dual" in this paper and is comprised of a VSD with forward-view terrain imagery, and a HSD with downward-view terrain imagery as shown in Fig. 35. The downward-view terrain image was actually drawn in perspective view, as opposed to plan-view, from an eye-point far above the helicopter. The eye-point height changed with the HSD scale. Though similar to a true-plan view, the downward-view perspective image showed the sides and top of vertical obstacles like wire poles (unless directly under the aircraft), while a true plan-view would have shown only the tops of obstacles. The VSD had a forward-view, earth referenced pitch ladder and flight path marker symbol not shown on the HSD, and it was intended to be used in high-speed flight. The HSD had a plan-view velocity vector, acceleration cue, target speed symbol, and target position symbol not shown on the VSD, and it was intended to be used in low-speed flight. Two Air Force pilots flew the HSD on the left display, while the Navy and USMC pilots flew the HSD on the right display to put the HSD directly in front of the pilot.

The second of the three symbol sets was developed by AFRL and is called "switched" in this paper (Figs. 36-37). For all pilots, the right display switched between a VSD and an HSD display at 30 knots ground speed. The intent of the switched display set was to enable the pilot to keep his eyes on a single display. The left display was an HSD display at all speeds for this display set, and it was redundant with the right display below 30 knots. Pilots commented that they did not use the left display for landing the aircraft.

Figure 38 shows the third variant of the BOSS symbol set, used only with FLIR terrain imagery in the background. This variant is called "single" in this paper, since only a single display was used. In the single display, both the forward-view flight path marker, and the plan view hover symbols were shown simultaneously above 20 knots. Below 20 knots the flight path marker symbol disappeared. With the single display, the pitch ladder was absent, but the horizon line remained on at all speeds. Only five landings were attempted with the single display configuration due to limited flight time, and the priority was the LADAR conditions over the FLIR conditions.

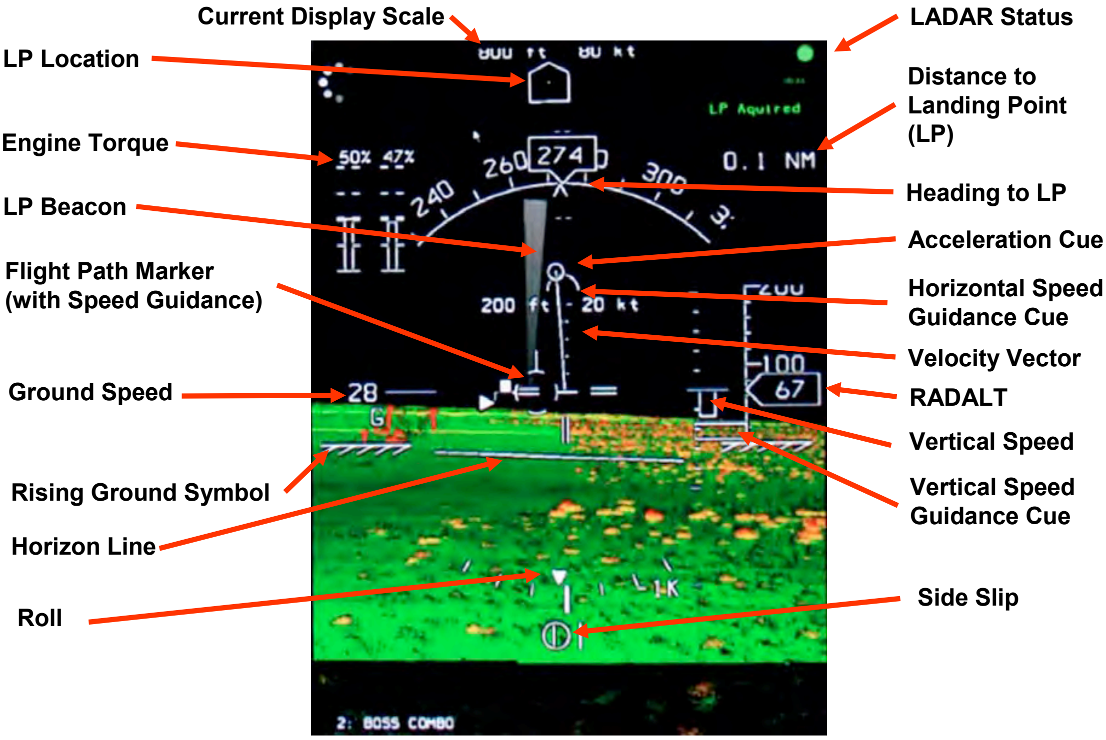


Fig. 33. BOSS Symbology

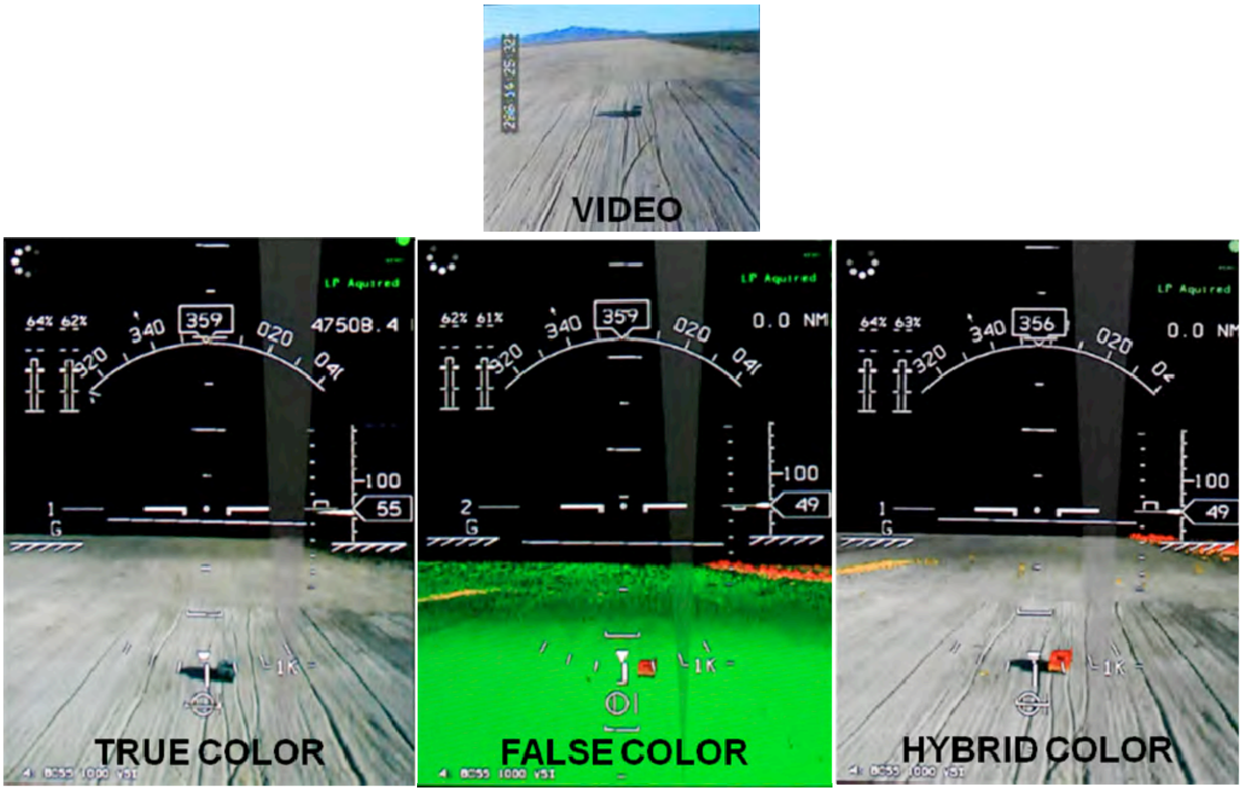


Fig. 34. Three types of output from LADAR which are operator selectable.

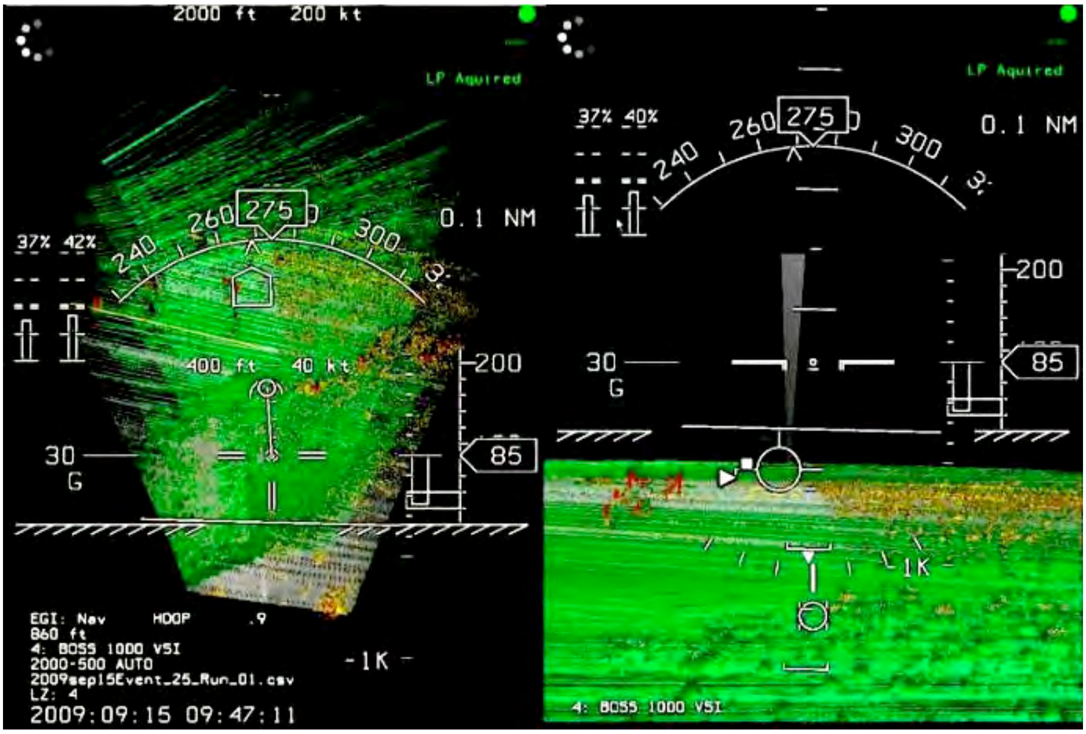


Fig. 35. Dual display with VSD on right and HSD on left.

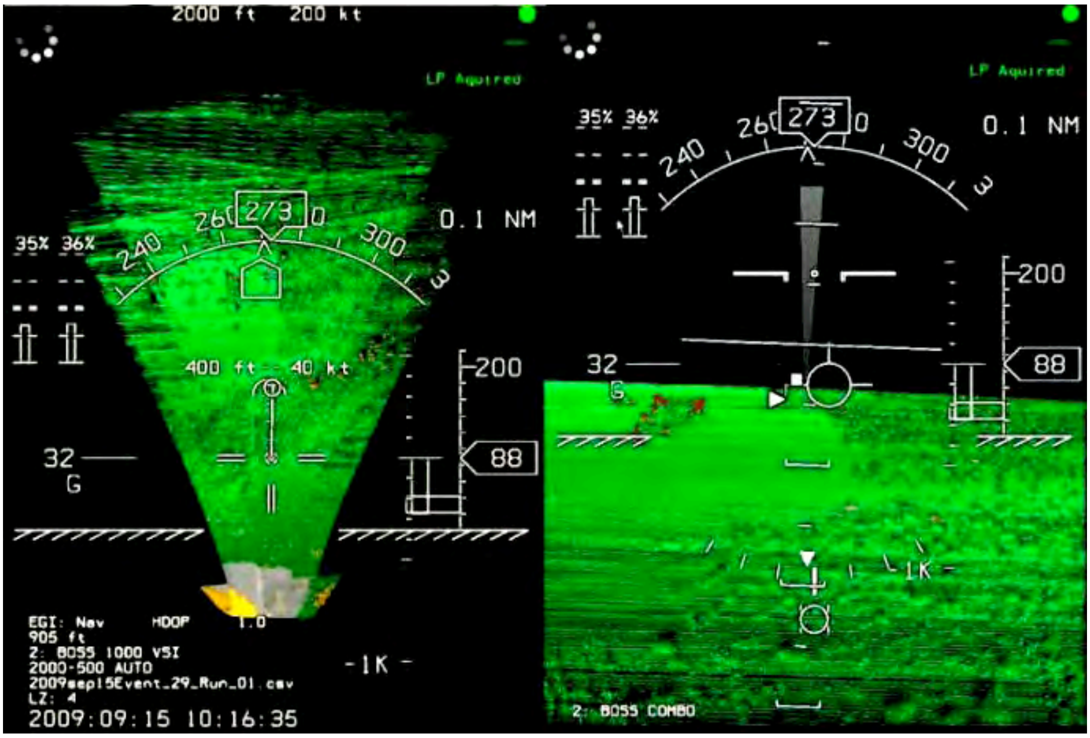


Fig. 36. Switched display (right) on high-speed page; left display stays as an HSD.

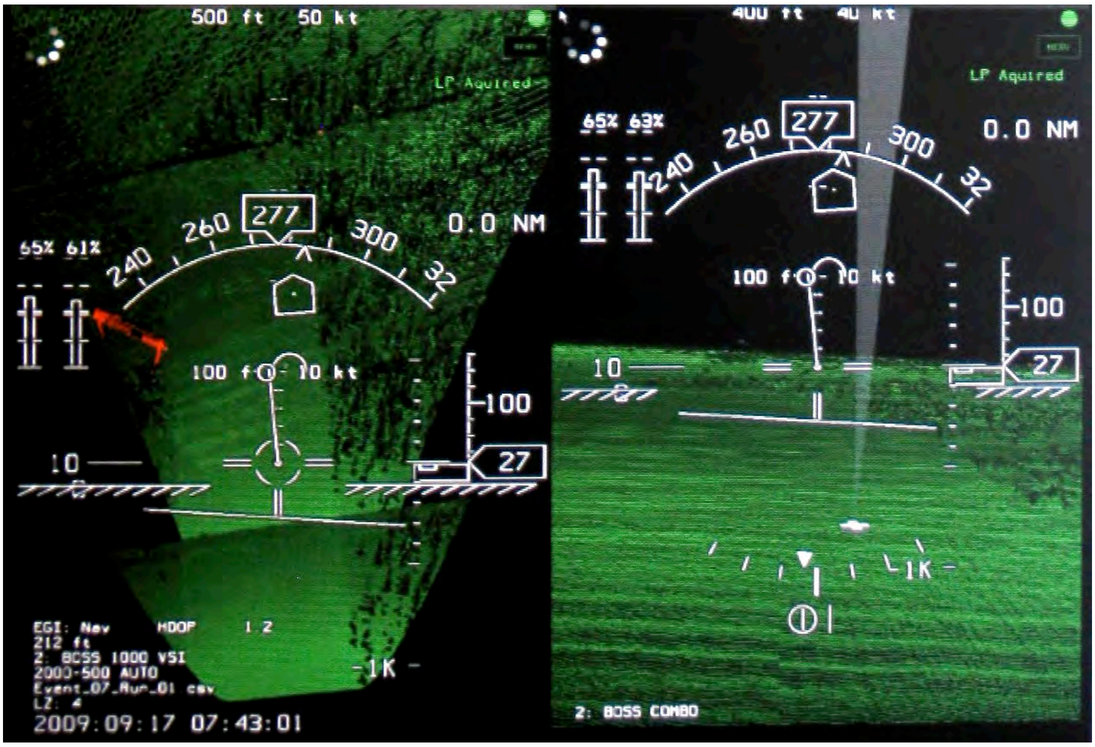


Fig. 37. Switched display (right) on low-speed page; left display stays as an HSD.

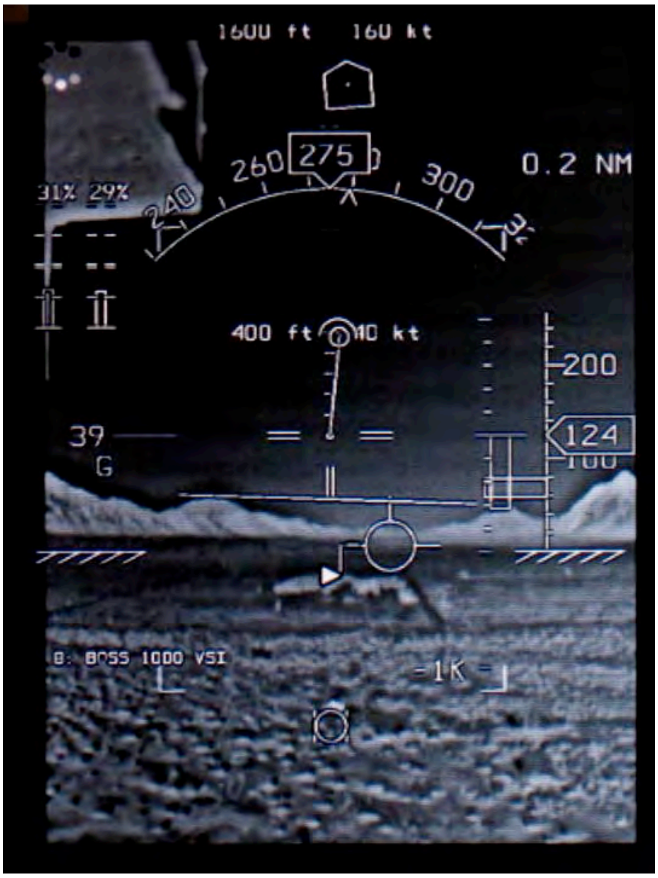


Figure 38. Single display was used only with FLIR terrain imagery.

Landing Maneuver Description

Landings at the YPG test site were all performed at prepared sites. All but three landings were conducted at the Oasis site, shown in Fig. 39, which was 500 ft long and 200 ft wide. The target landing point was deliberately offset 50 ft to the north (right on photo) to increase the distance from the telephone poles, wires, and other ground obstacles. Three landings were conducted at an alternate prepared site due to lingering dust clouds at the Oasis site. Both sites were plowed to increase the quantity of dust during landing (Fig. 40).

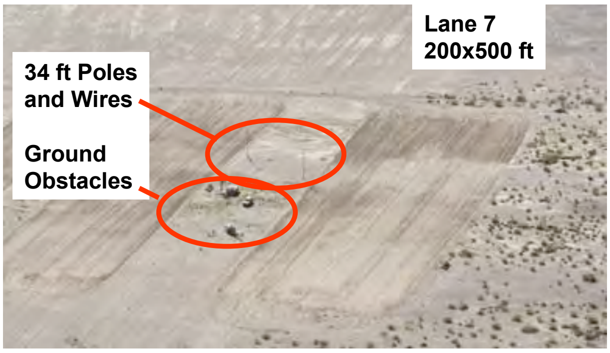


Fig. 39. Landings were conducted primarily in lane 7 at the Yuma Proving Ground dust course.

Fig. 40. Lanes were plowed to increase quantity of dust (EH-60L shown).

Landing maneuvers were started at approximately 250 foot altitude, 80 knots ground speed, and 1-2 nautical miles from the landing point. Speed guidance started at 0.8 nm, at which point the pilot both started the deceleration and started the descent. All landings were conducted with the pilot's feet off the pedals, using the heading hold function of the aircraft to maintain heading. The two developmental pilots thought that the original 25 knot scale (to the top of the screen) on the plan-view velocity vector caused too much workload. Therefore, the evaluation pilots all flew the 50 knot velocity vector scale for the landing maneuver.

All approaches started with the evaluation pilots using the out-the-window view of the terrain. Pilots were free to switch back and forth between the out-the-window view and the panel mounted displays during the approach, before the brownout condition. Pilots chose the time to shift their attention solely to the panel-mounted displays; this was always done before entering the brownout. In the case of the dual display, pilots switched their attention from the VSD to the HSD at a time of their choosing. Table 1 lists the desired and adequate maneuver parameters for touchdown.

Table 1. Maneuver standard for landings

Variable	Desired	Adequate	Measure
Vert. Velocity	$\leq$150	$\leq$300	ft/min
Fwd. Speed	$\leq$5	$\leq$10	knots
Aft Speed	$\leq$0.5	$\leq$1.0	knots
Lat. Speed	$\leq$0.5	$\leq$1.0	knots
Heading	No Req.	No Req.	-
Position Error	$\leq$50	$\leq$100	ft
Time	No Req.	No Req.	-

Hover Maneuver Description

Two evaluation pilots flew hover over load maneuvers. The maneuvers began with an approach from approximately 250 ft altitude, 80 knots ground speed, and 1-2 nautical miles from the landing point. Speed guidance started at 0.8 nm, at which point the pilot both started the deceleration and started the descent. All approaches were done with the pilot's feet off the pedals; the heading hold function of the aircraft was used. There were no changes for horizontal speed guidance from the landing maneuver. The initial hover point symbol (same as the landing point symbol) was deliberately offset from the load.

Descent angles were set early in the approach using the out-the-window view. By tracking the target altitude symbol with the end of the vertical speed tape, the pilots would command the aircraft to asymptotically converge to the 50 ft target altitude. Typically, pilots arrived at the target altitude before they arrived at the target position.

Once in a hover at the initial hover point offset from the load, the target altitude symbol was changed from 50 ft to either 35 ft or 30 ft (depending on the load) by the system operator. Two methods were used for the reposition over the load.
1) In the first method, pilots would manually move a temporary hover point symbol, which was shown dashed, over the downward-view LADAR image of the load using a two-axis switch on the collective control. The original hover point symbol continued to be drawn in solid lines. Once the temporary hover point symbol was in the correct position on the display, the pilot pressed an "accept" switch also on the collective control. At that time, the original hover point symbol disappeared, and the temporary hover

point symbol became the new hover point, drawn with solid lines.
2) The second method used for the reposition over the load was to use the image of the load as the target; the pilot manipulated the cyclic to place the acceleration cue symbol over the image of the load, while ignoring the original hover location marked by the target hover point symbol.

For the reposition maneuver, the evaluation pilot moved forward to the new hover point, and then descended to the new target altitude (Fig. 41). Once the reposition task was completed, the evaluation pilot would call "stable", the 20 second clock was started, and the pilot would try to maintain a hover over the load within to the maneuver limits listed in table 2 to simulate a hook-up of the external load. No cables were used.

Figure 41. EH-60L in hover over load.

Table 2. Maneuver standard for hover over load task

Variable	Desired	Adequate	Measure
Position	+/-2	+/-5	feet
Heading	+/-3	+/-5	deg
Altitude	+/-3	+/-5	feet

Pilot Demographics

All evaluation pilots were military trained rotorcraft pilots. Four pilots flew the landing maneuver. The Marine Corp. and Navy pilot also flew the hover maneuver. Table 3 lists their experience. The safety pilot for all flights was a US Army test pilot from AFDD. An Army AATD test pilot also flew for initial check-out and set-up.

Table 3. Evaluation pilot experience

Service	Exp. Test Pilot	Primary Aircraft	Rotary Wing Hours	Brownout Experience
Air Force	No	HH-60G	2,000	Yes
Air Force	Yes	CV-22	1,600	No
Marine Corps	Yes	CH-53	1,600	Yes
Navy	Yes	MH-60S/R	1,350	Yes

Results and Interpretation

Landing Maneuver.

Objective Results. Safe landings were accomplished on 77% of the attempts with the LADAR (20 out of 26). Safe go-around maneuvers by the evaluation pilot were demonstrated on the remaining 23% of the attempted landings. Safe landings were accomplished on 3 of the five attempts with the FLIR sensor and single display symbol set. Five out of the eight go-around maneuvers were called for by the safety pilot. The cause of the go-around was lateral drift (4 times), aft drift (2 times) excessive forward speed (one time), and one case of a large collective input close to the ground.

Figures 42-48 show the objective data measured during landing. With only four evaluation pilots, an Analysis of Variance (ANOVA) was not practical to implement. For the landing maneuver, the exact time of touchdown could not be determined from the aircraft state data in post-flight analysis. This was due to the soft soil at the landing site, shock absorbers on the wheels, vibration noise in the acceleration signals, as well as drift and noise in the aircraft radar altimeter. In the data analysis, there is an assumption that the values of vertical speed, lateral speed, and longitudinal speed reduce in absolute value once the first wheel touches the ground. Rather than take a single point in time, maximum values of speed in all three axis were determined for a range of radar altitudes. The lower end of the range was determined by finding the lowest common radar altimeter reading for all landings, which was -1 ft. The upper limit was set at 3 ft above the lower the limit, which was +2 ft. The selected range might not capture the wheel-touch event for some of the landings; it was better to err on the high side (entire range may be before touchdown) than err on the low side (entire range may be after touchdown).

Figure 42 shows the highest vertical speed (in the down direction), for the aircraft between +2 and -1 ft radar altitude. First occurrences of +2 ft and -1 ft were used to define the range. The desired boundary of 150 ft/min and the adequate boundary of 300 ft/min are shown. The actual landing gear limit for the Black Hawk in the weight range of the test aircraft is 540 ft/min for flat terrain and 360 ft/min for sloped terrain. As shown in Fig. 42, the aircraft was within desired tolerances (or borderline) for most of the landings. Only two landings were slightly into the adequate range; the highest vertical speed was 176 ft/min. There is a trend toward more consistent vertical speeds between landings with the dual display, as shown in Fig. 42.

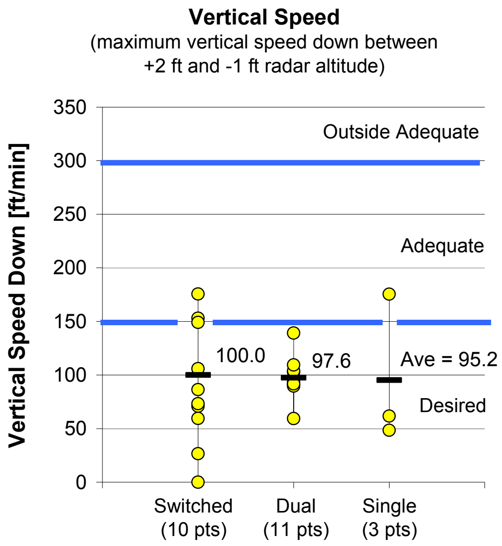


Fig. 42. Vertical speed.

Figure 43 shows the data for the highest lateral speed between +2 ft and -1 ft radar altitude. Tolerances for lateral speed were very tight: 0.5 knot desired, and 1.0 knot for adequate. Eight of the landings were within the desired range, eleven were within the adequate range, and four of the landings were slightly outside the adequate range. The highest lateral speed measured was 1.16 knots, which is slightly outside of adequate. At no time did the safety pilot feel the aircraft was close to a roll-over. The reduction in lateral speed caused by the aft gear touching before the forward main gears (the standard UH-60 landing) is not seen in the data, since worst case speeds were recorded before touchdown. In retrospect, video recording of the landing gears would have enabled the analysis of lateral speed to be broken up into speeds before the aft wheel touchdown event, and speeds before the main wheel touchdown event.

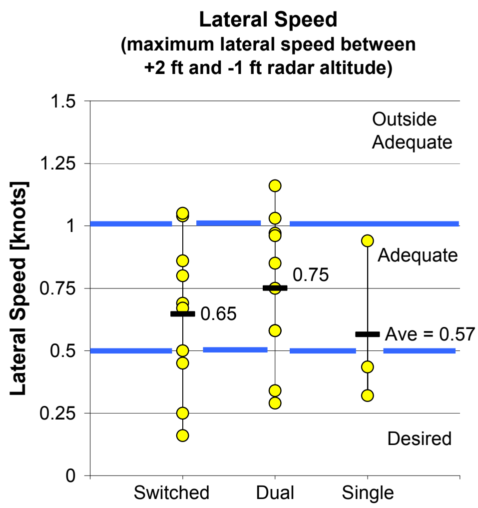


Fig. 43. Lateral speed.

Figure 44 shows the highest forward speed between +2 ft and -1 ft radar altitude. Twenty landings were within the desired tolerance (or borderline), which was less than 5 knots ground speed; three landings were in the adequate range, which was less than 10 knots ground speed. The highest forward speed was 8.4 knots, with the single display condition.

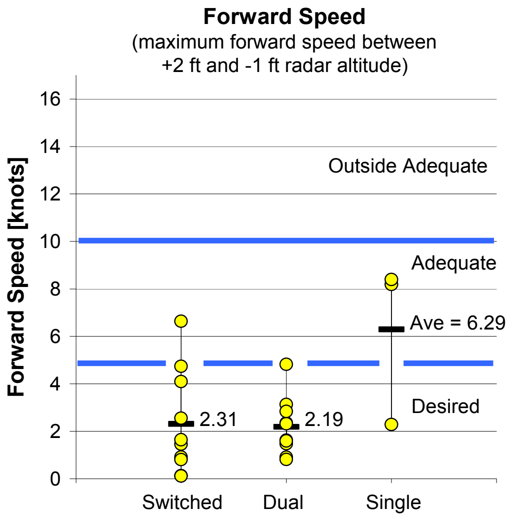


Fig. 44. Forward speed.

Figure 45 shows the maximum speed in the aft direction between +2 ft and -1 ft radar altitude. For 14 of the 23 landings, the aft speed was zero. In nine cases, the aircraft came to a hover near the ground, and then began drifting aft slowly between +2 and -1 ft radar altitude. Nineteen landings had aft speed in the desired range, three landings had aft speed in the adequate range, and one was borderline between adequate and outside of adequate at 0.97 knots.

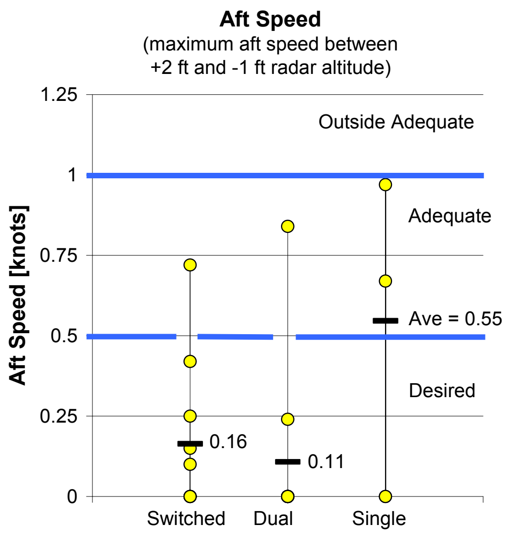


Fig. 45. Aft speed.

Figure 46 shows the position of the aircraft at the first occurrence of the radar altimeter going through -1 ft, as measured by the aircraft Embedded GPS/Inertial navigation system (EGI) which drove the symbols. This diagram does not include errors in the measurement of aircraft position, but rather it shows of how close pilots were able to put the aircraft own-ship symbol onto the target landing point symbol. The position data charts do not include three landings which were conducted at a different site due to lingering dust at the primary test site. The previous speed charts (Figs. 42-45) do include data from the alternate site.

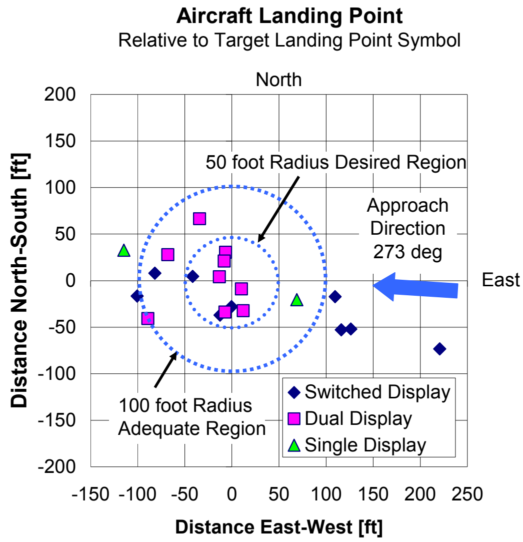


Fig. 46. Landing position (at -1 ft radar altitude) relative to target landing point as measured by EGI and displayed to the pilot.

Figure 47 shows the lateral position error for a 273 degree true heading desired ground track. All but two landings were within the desired 50 ft error. The two largest errors were 61.6 feet with the switched display and 64.5 feet with the dual displays.

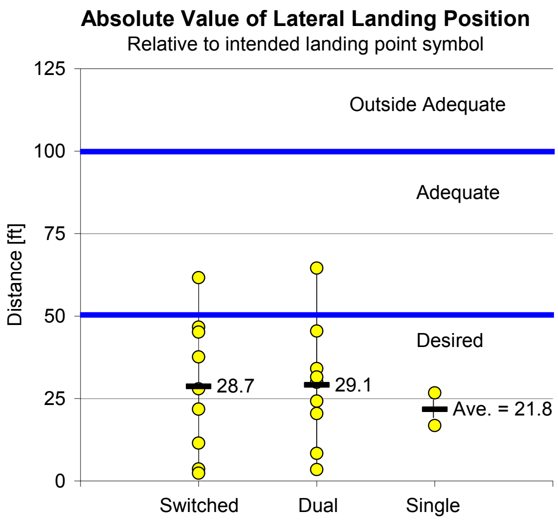


Fig. 47. Lateral position error.

Figure 48 shows the longitudinal position error for a 273 degree true heading desired ground track. The average position error for the dual display configuration was one third the average error for the switched and single displays. Some pilots stated that they intentionally had forward speed at touchdown, which affected longitudinal position precision. Also, the observation was made that pilots did prioritize the different landing criteria, and they allowed longitudinal position error to suffer in order to have better control of lateral speed, lateral position, and vertical speed. The pilots were aware that there were no obstacles in front of the aircraft in the landing lane.

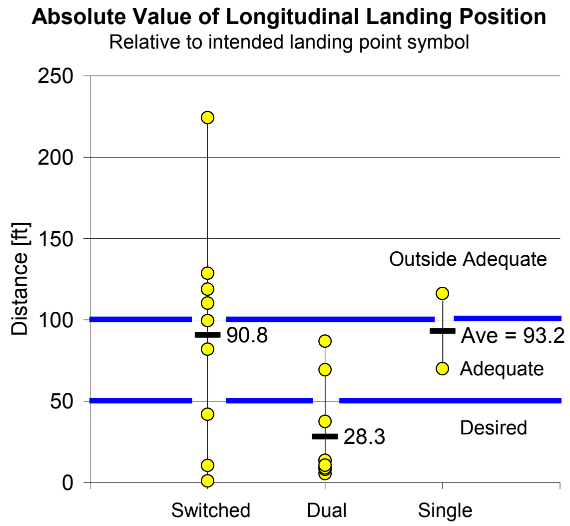


Fig. 48. Longitudinal position error.

Subjective Results. Figure 49 shows the histogram of how the four evaluation pilots ranked their most preferred display. Only one condition was rated as most desired by two pilots. That condition was the single display.

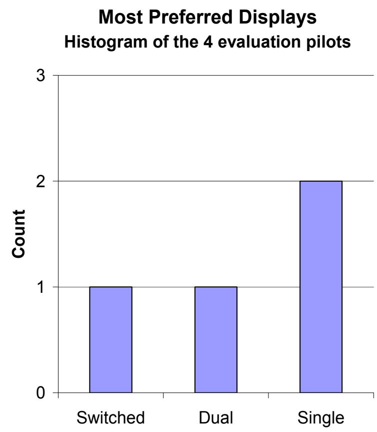


Fig. 49. Display preference for the 4 evaluation pilots.

Figure 50 shows the average HQR ratings for the three displays, which ranged between a rating of 4.3 (dual display) and 5.5 (single display)(Refs. 20-23, Appendix A). A lower score indicates better handling qualities. Each pilot's individual scores were averaged before the four pilot's scores were averaged, so that each pilot had equal weight. Note that the best HQR rating was for the dual display configuration. One of the purposes of Fig. 50 is to establish the handling quality level for the task. For all display configurations, the HQR ratings were in the level 2 handling quality range.

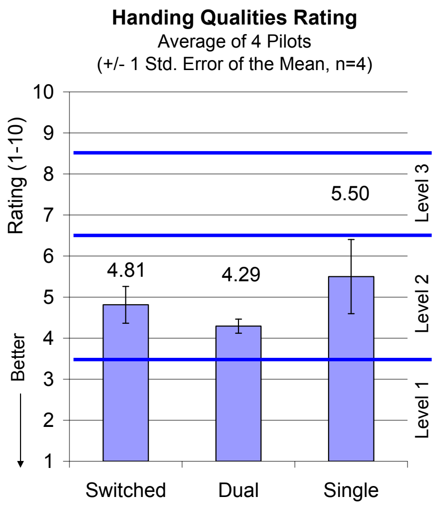


Fig. 50. Average HQR.

Figure 51 shows the histogram of the HQR for the four evaluation pilots. As shown in the figure, ratings clustered around an HQR of 4 and 5 which are defined as follows:

> HQR 4: Minor but annoying deficiencies. Desired performance requires moderate pilot compensation.
>
> HQR 5: Moderately objectionable deficiencies. Adequate performance requires considerable pilot compensation.

In Fig. 51, the dual display configuration stands out as not having any HQR values higher than 5 for any landings. The other two displays had at least one occurrence of an HQR higher than 5.

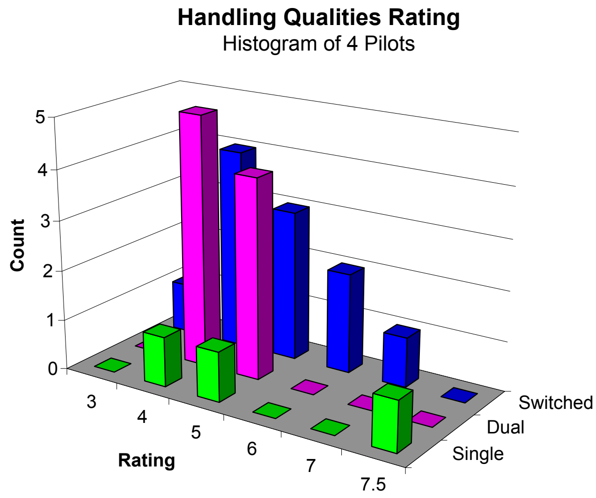


Fig. 51. Histogram of HQR

As suggested in the test guide for ADS-33 (Ref. 22), the VCRs for the pilots are tabulated as shown in tables 4-6. Each pilot's score was averaged before it was inserted in the table, to give each pilot equal weight. The VCR scales are shown in Appendix A.

Table 4. Visual Cue Rating for the Switched Display, Landing Maneuver

	Attitude	Horiz. Trans. Rate	Vertical Trans. Rate	Worst Case of H & V Trans. Rate
Pilot A	3.00	1.50	2.75	2.75
Pilot B	2.25	2.75	3.00	3.00
Pilot C	3.00	2.00	2.00	2.00
Pilot D	2.00	2.00	2.00	2.00
Average	2.56			2.44
Std Dev Pop.	0.45			0.45

Table 5. Visual Cue Rating for the Dual Display, Landing Maneuver

	Attitude	Horiz. Trans. Rate	Vertical Trans. Rate	Worst Case of H & V Trans. Rate
Pilot A	4.00	1.50	3.00	3.00
Pilot B	3.00	2.67	2.00	2.67
Pilot C	3.00	2.00	2.00	2.00
Pilot D	2.00	3.00	3.00	3.00
Average	3.00			2.67
Std Dev Pop.	0.71			0.41

Table 6. Visual Cue Rating for the Dual Display, Landing Maneuver

	Attitude	Horiz. Trans. Rate	Vertical Trans. Rate	Worst Case of H & V Trans. Rate
Pilot A	-	-	-	-
Pilot B	3.00	3.00	3.00	3.00
Pilot C	3.00	2.50	2.50	2.50
Pilot D	2.00	3.00	3.00	3.00
Average	2.67			2.83
Std Dev Pop.	0.47			0.24

Figure 52 plots the average VCR scores, with the Usable Cue Environment (UCE) criteria boundaries. As can be seen in the figure, the three display configurations have ratings that are very close to each other, and are solidly in the UCE=2 region. ADS-33 suggests that handling qualities could improve by augmenting the flight control system from a rate-command direction-hold to an attitude-command attitude-hold system (Ref. 21).

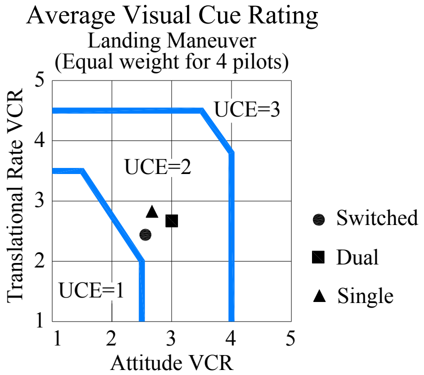


Figure 52. Average VCR plotted on Usable Cue Environment criteria boundaries for the landing maneuver

Figure 53 shows the result of the Task Load Index (TLX) questionnaire (Ref. 23). A lower score is interpreted as lower workload. Each pilot's scores were given equal weight. As can be seen, there was little difference in the average scores between display configurations. Pilots commented that workload were very high. Figure 53 indicates that workload was nearly equally very high for all display configurations.

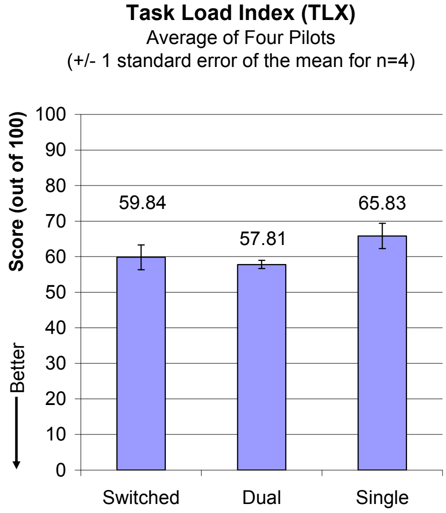


Fig. 53. Average NASA-TLX rating.

Figure 54 shows the average score for each of the six dimensions of the TLX questionnaire. Since there was little difference in TLX scores between display conditions (Fig. 53), the scores in Fig. 54 were averaged across display conditions, and each pilot was given equal weight. The three worst scores were: mental demand, temporal demand, and effort. The three best scores were physical demand, performance, and frustration. The interpretation of the component scores is that a reduction in workload can best be achieved through a reduction in mental demand and temporal demand as opposed to a reduction in physical demand, improvement in performance or a reduction of the frustration of the task.

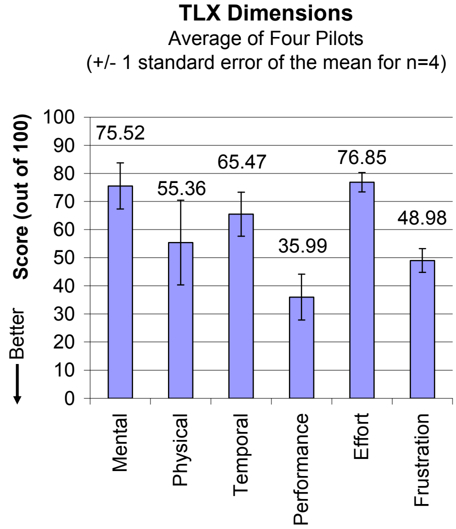
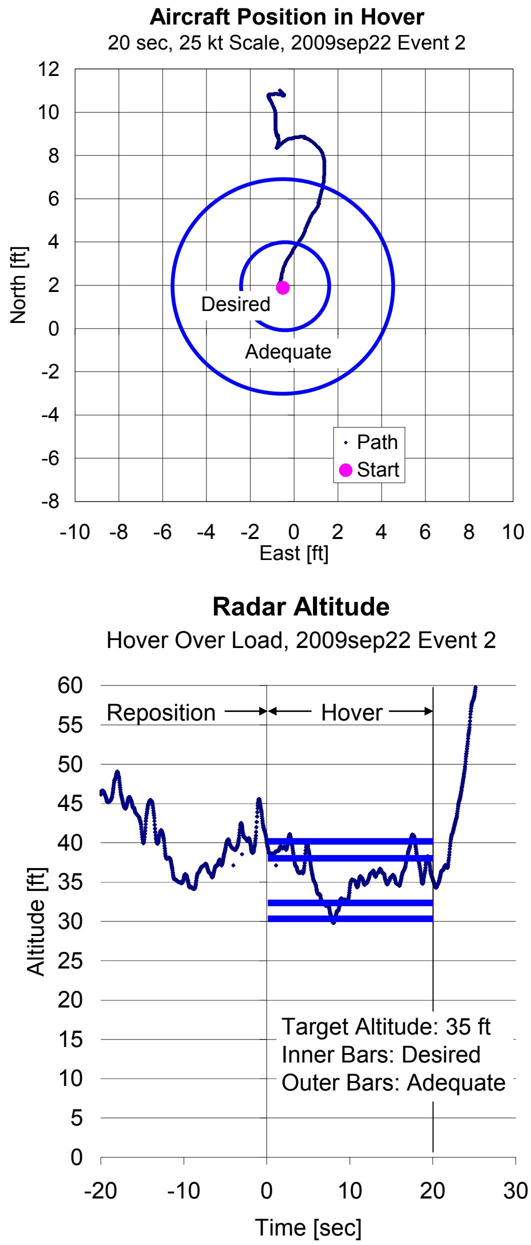


Fig. 54. Average scores for the TLX dimensions.

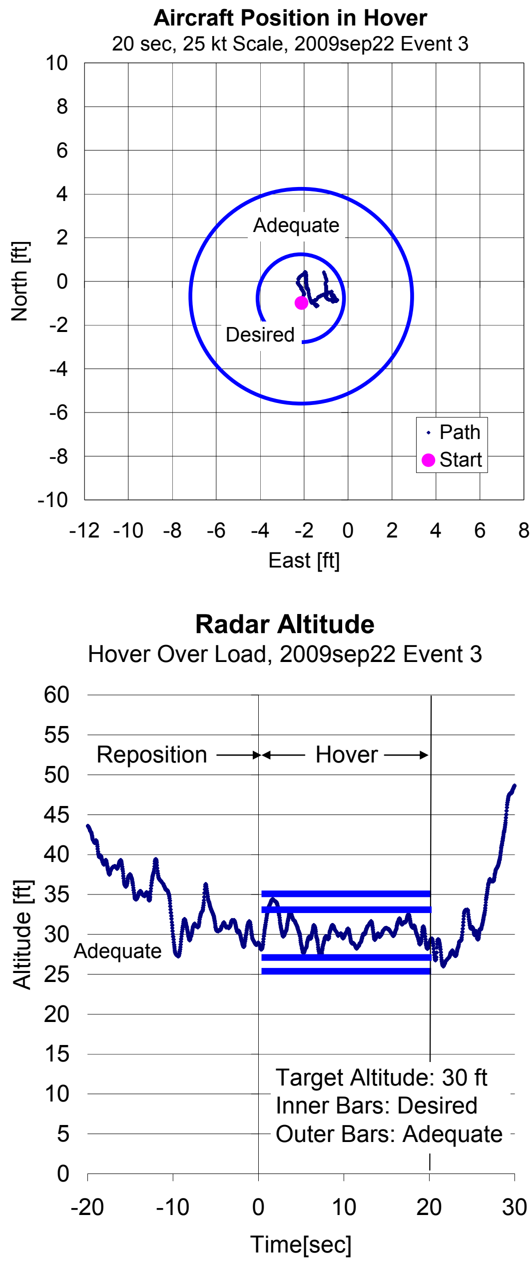
Hover Maneuver

Objective and Subjective Results. Figures 55-65 show the objective and subjective data for the hover over load maneuver. Since the displays were nearly identical at low speeds, the data is not categorized by display types.



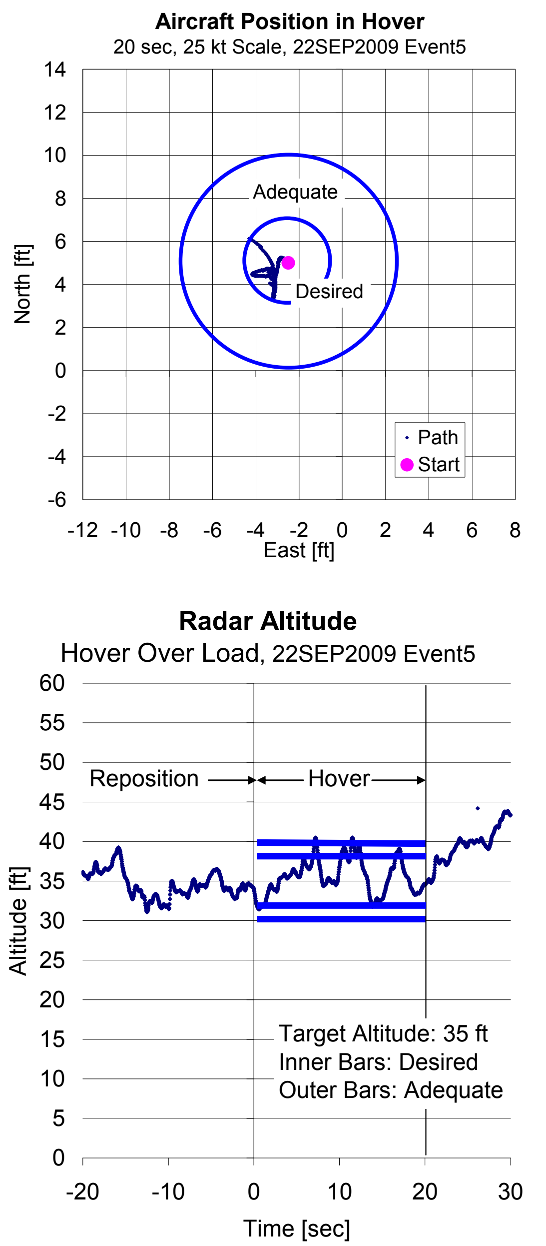
Sep 22, Event 2				
	HQR	Att VCR	Horiz. Trans. Rate VCR	Vert. Trans. Rate VCR
Hover	7	3	3	3

Fig. 55. Reposition and hover, Sep 22, event 2.



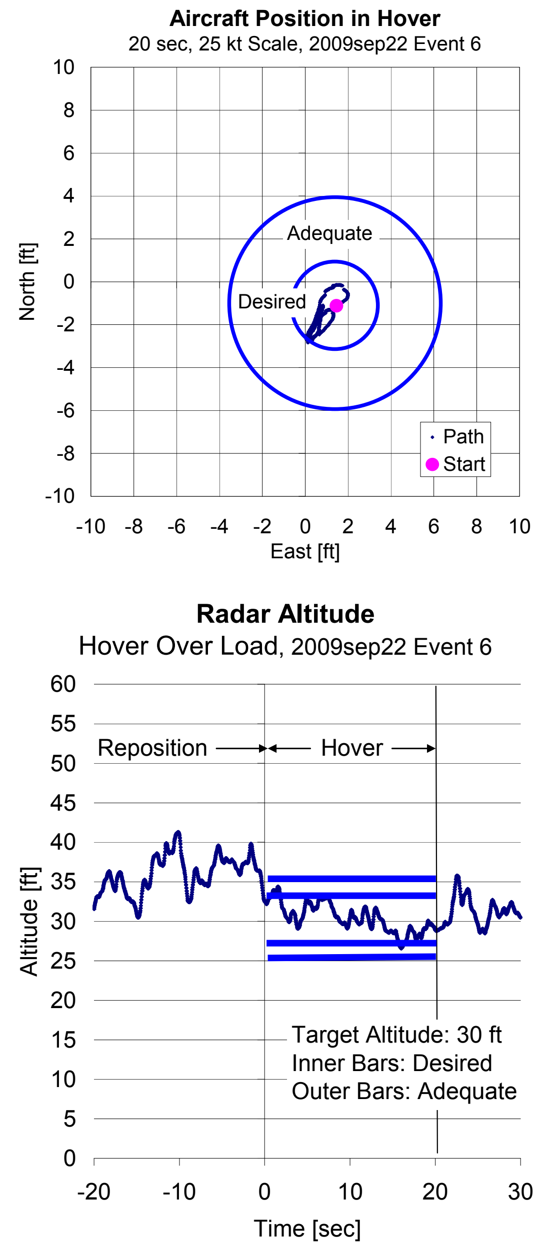
Sep 22, Event 3				
	HQR	Att VCR	Horiz. Trans. Rate VCR	Vert. Trans. Rate VCR
Hover	4	3	3	3

Fig. 56. Reposition and hover, Sep 22, event 3.



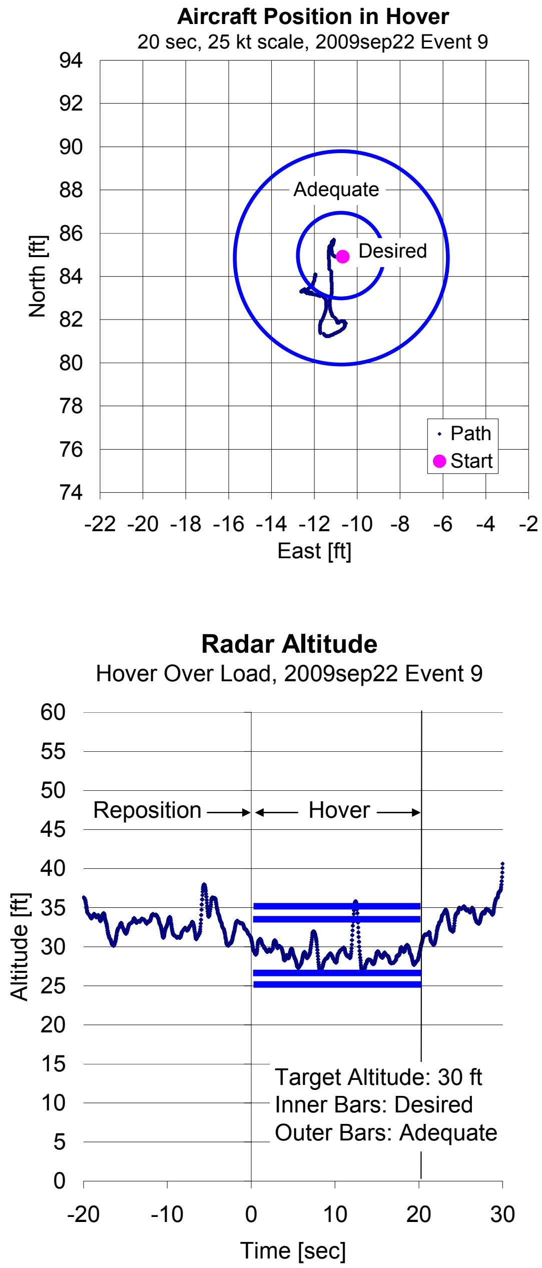
Sep 22, Event 5				
	HQR	**Att VCR**	**Horiz. Trans. Rate VCR**	**Vert. Trans. Rate VCR**
Hover	5	3	3	3

Fig. 57. Reposition and hover, Sep 22, event 5.



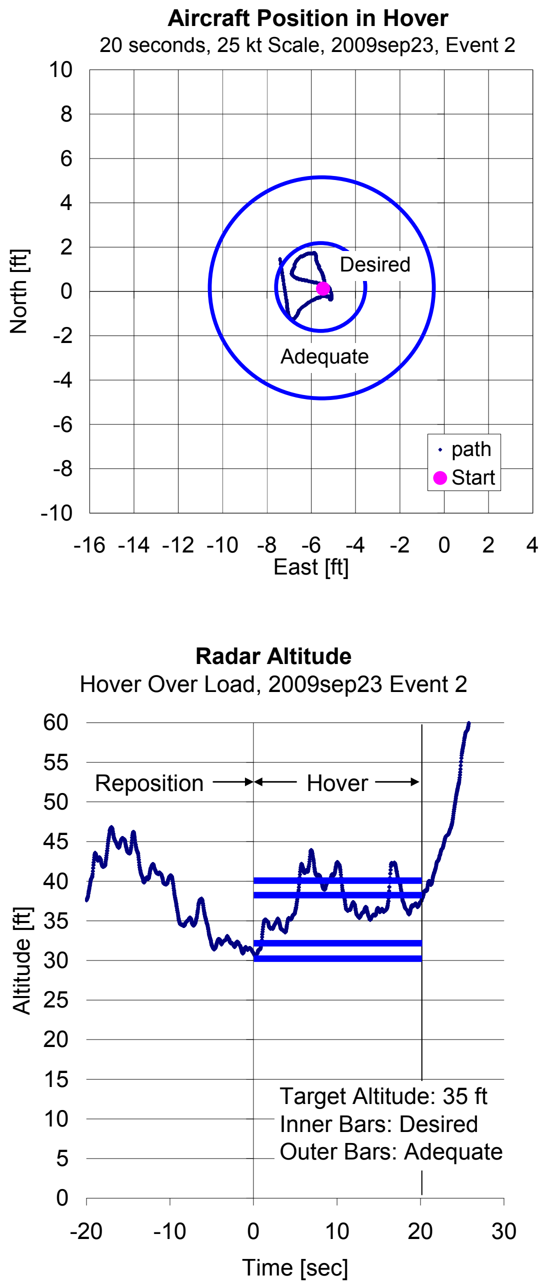
Sep 22, Event 6				
	HQR	**Att VCR**	**Horiz. Trans. Rate VCR**	**Vert. Trans. Rate VCR**
Hover	5	3	3	3

Fig. 58. Reposition and hover, Sep 22, event 6.



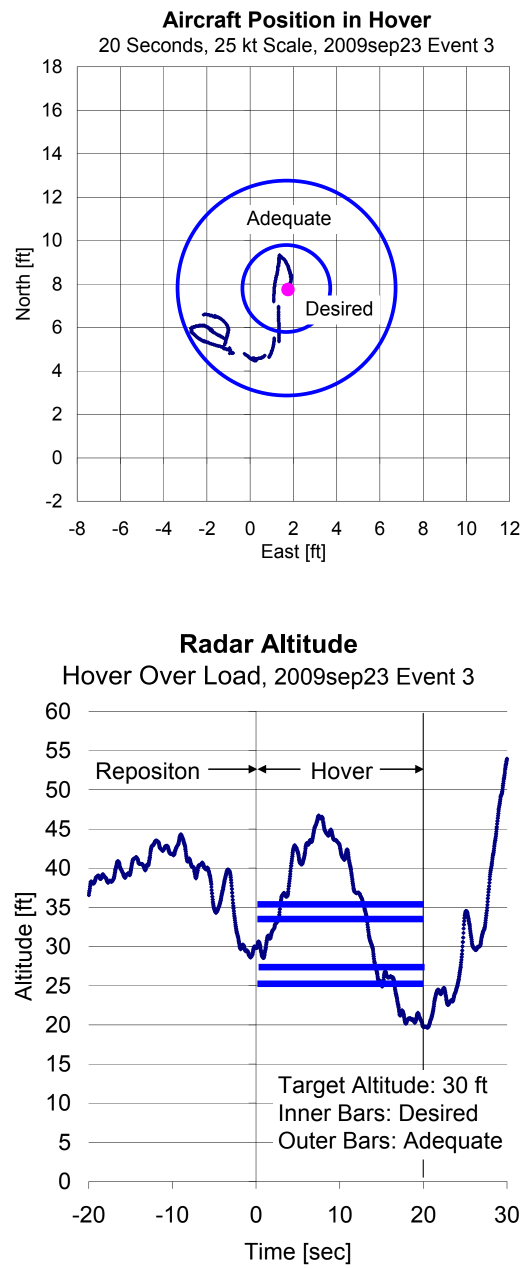
Sep 22, Event 9				
	HQR	**Att VCR**	**Horiz. Trans. Rate VCR**	**Vert. Trans. Rate VCR**
Hover	4	3	2	2

Fig. 59. Reposition and hover, Sep 22, event 9.



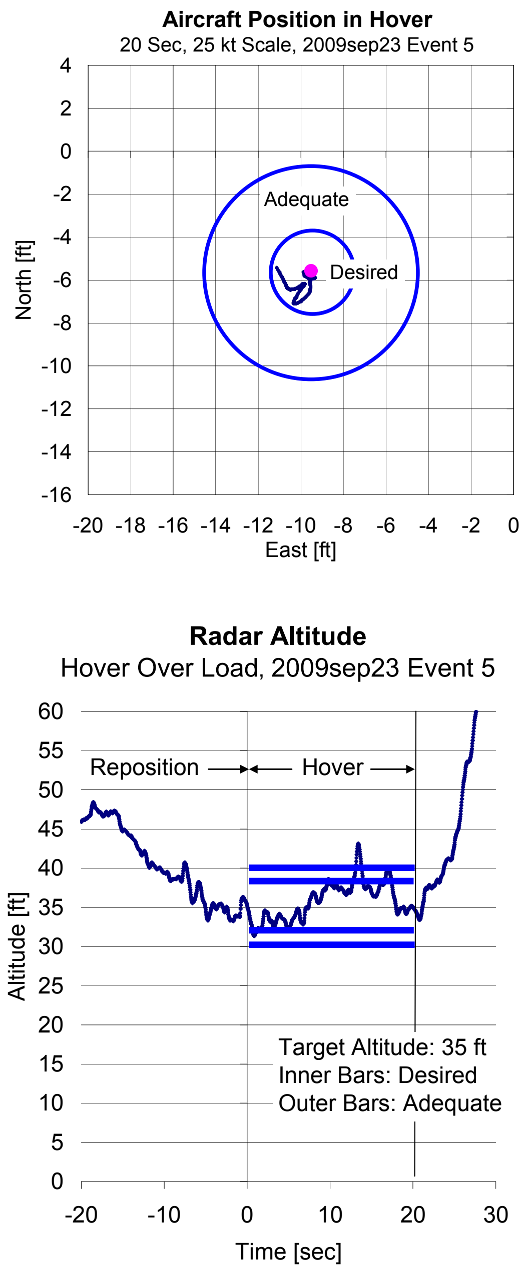
Sep 23, Event 2				
	HQR	**Att VCR**	**Horiz. Trans. Rate VCR**	**Vert. Trans. Rate VCR**
Hover	5 Due to z-axis	2	2	4

Fig. 60. Reposition and hover, Sep 23, event 2.



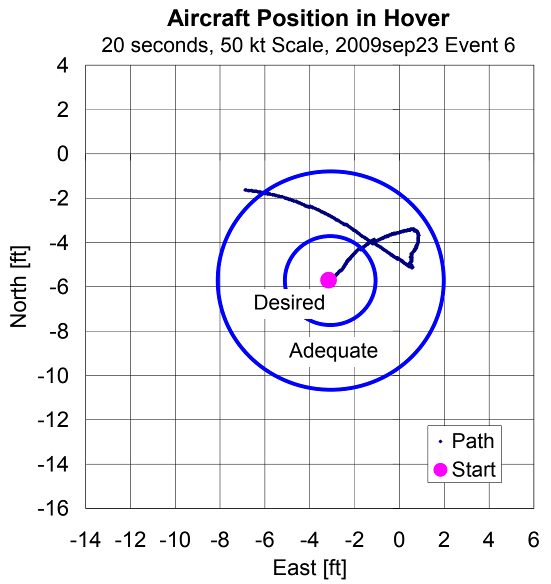
Sep 23, Event 3				
	HQR	**Att. VCR**	**Horiz. Trans. Rate VCR**	**Vert. Trans. Rate VCR**
Hover	7 Due to z-axis	2	2	4

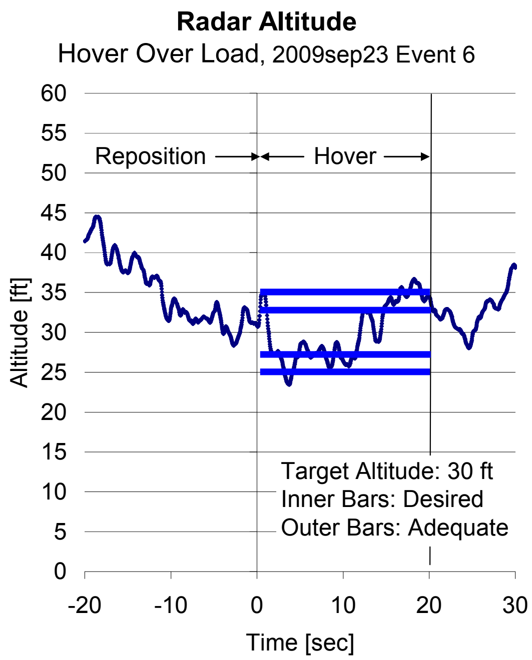
Fig. 61. Reposition and hover, Sep 23, event 3.



Sep 23, Event 5				
	HQR	**Att. VCR**	**Horiz. Trans. Rate VCR**	**Vert. Trans. Rate VCR**
Hover	6 Due to z-axis	2	2	4

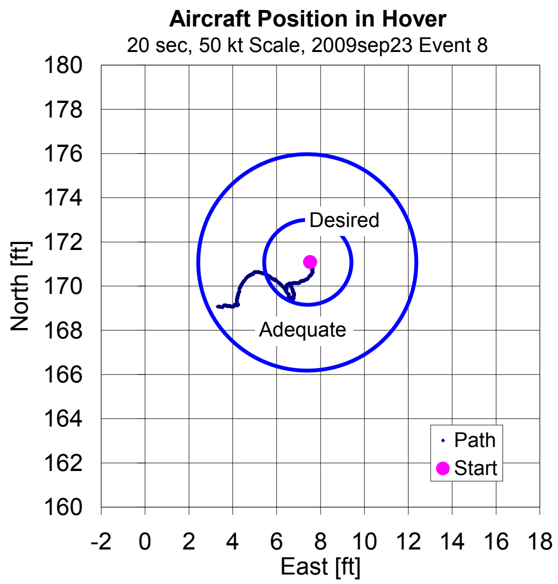
Fig. 62. Reposition and hover, Sep 23, event 5.

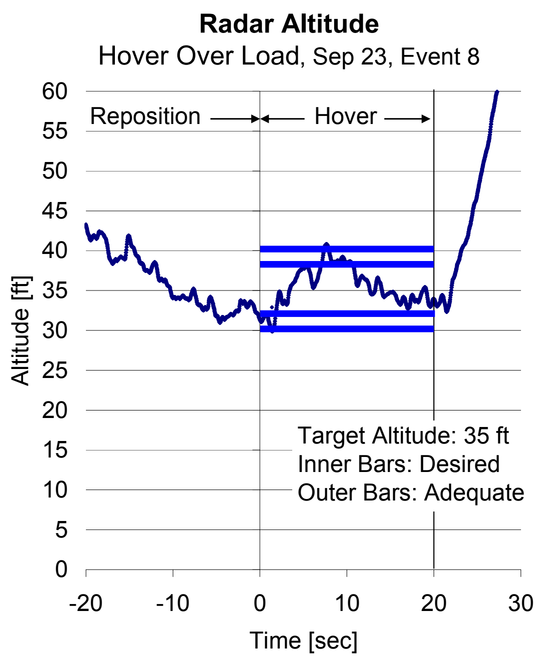




Sep 23, Event 6				
	HQR	**Att VCR**	**Horiz. Trans. Rate VCR**	**Vert. Trans. Rate VCR**
Hover	6 Due to z-axis	2	1	4-5

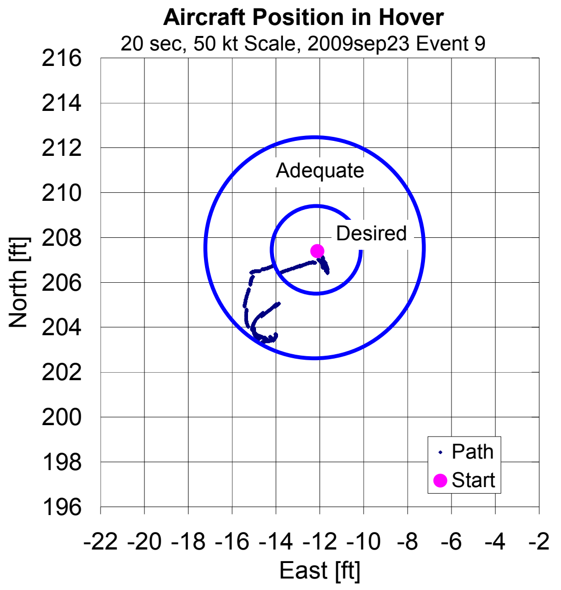
Fig. 63. Reposition and hover, Sep 23, event 6.

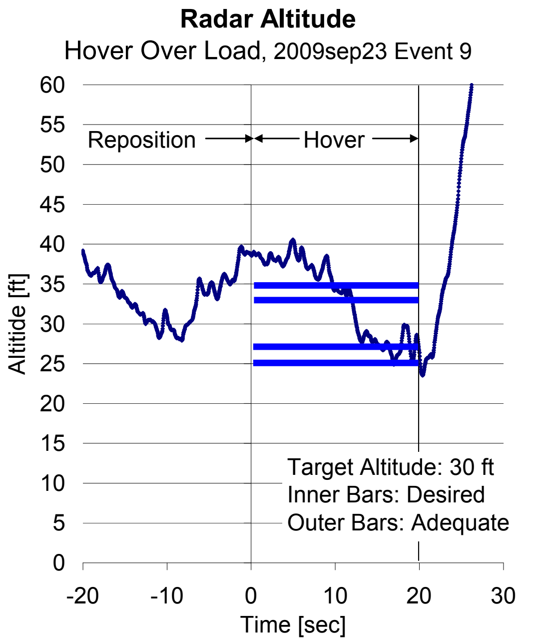




Sep 23, Event 8				
	HQR	**Att VCR**	**Horiz. Trans. Rate VCR**	**Vert. Trans. Rate VCR**
Hover	5 Due to lateral axis	2	3	3

Fig. 64. Reposition and hover, Sep 23, event 8.





Sep 23, Event 9				
	HQR	**Att VCR**	**Horiz. Trans. Rate VCR**	**Vert. Trans. Rate VCR**
Hover	6 z 5 x-y	2	3	4-5

Fig. 65. Reposition and hover, Sep 23, event 9.

Most of the hover over load maneuvers were performed with the 25 knot scale to the top of the screen. One of the two pilots switched to the 50 knot scale to see if the change would improve the HQR rating while maintaining position accuracy. There were only three hover attempts at the 50 knot scale, and only adequate performance was obtained in position control with the less sensitive scale. Handling Qualities Ratings were 6, 5, and 5.5 for these three attempts, and were 5.4 on average on the other hovers.

As the hover over load data shows (Figs. 55-65), the position was maintained within desired performance (except for short, small excursions) 5 of 11 times, and always with the 25 knot scale. Adequate performance occurred also 5 of 11 times (twice with the 25 knot scale, three times with the 50 knot scale). Outside adequate performance occurred one time with the 25 knot scale. Improvements in hover position could be obtained by augmenting the flight control system to include a position hold feature.

For altitude, desired performance (+/-3 ft) was accomplished three times, adequate performance (+/-5 ft) was accomplished four times, and outside adequate performance (>5 ft) was recorded four times. Improvements in hover altitude could be obtained by having a more sensitive vertical velocity scale. There is probably a mismatch in ideal scales; a 500 ft/min scale probably would have been better for the hover, while the 1000 ft/min scale seemed best for landing, take-off, and the traffic pattern. An altitude hold feature in the flight control system could also have made the task more precise.

Figure 66 shows the histogram of the HQR ratings for the hover over the load task. Giving each pilot equal weight, the average HQR was 5.42 which is level 2 handling quality. The average attitude VCR was 2.50. The worst case translational rate (horizontal or vertical) was 3.40.

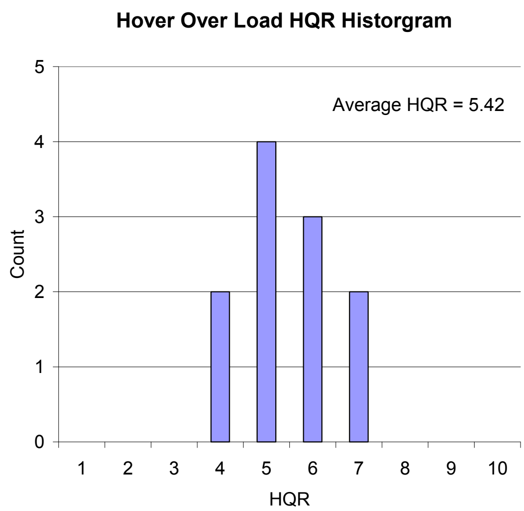


Fig. 66. Histogram of HQR for the hover over load maneuver.

Figure 67 plots the average VCR scores, with the UCE criteria boundaries. As can be seen in the figure, the rating is in the UCE=2 region. As with the landing maneuver, ADS-33 suggests that handling qualities could improve by augmenting the flight control system from a rate-command direction-hold to an attitude-command attitude-hold system (Ref. 21). Hover position hold and altitude hold features could also make the task more precise and reduce workload.

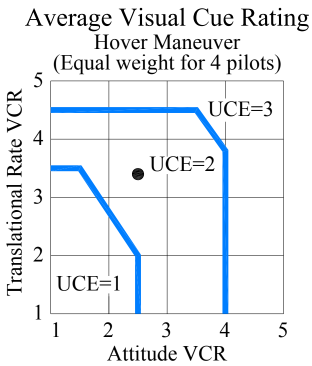


Fig. 67. Average VCR plotted on Usable Cue Environment Criteria boundaries for the hover over load maneuver

Pilot Comments

The major pilot comments are summarized as follows:

1) The system (LADAR and symbology) worked reasonably well, and it was better than what the pilots had in their fleet aircraft.
2) Workload was very high.
3) The presentation of small obstacle data on the display is an area that still needs improvement.
4.) Pilots were very positive about having obstacle imagery on the display throughout the landing, and saw the usefulness of the imagery for take-off.

Specific quotations from the pilots are provided below:

Landing Maneuver Comments

"I really like the system and quickly gained confidence in my ability to operate at low speed and land without visual references. Due to the controllability from the symbology and the SA [situational awareness] afforded by the LADAR picture, I found that I could confidently land in proximity to obstacles, such that I would not attempt with blindly coupled landing systems. The symbology was far more comfortable to fly than what I am used to in the CV-22. The vertical speed guidance, rising terrain [symbol], and cup/ball [horizontal] speed cues were key components that greatly reduced pilot workload and enabled a very controlled approach. The false coloring was intuitive and effectively alerted the pilot to the presence of and proximity to tall hazards such as the phone poles and wires in Oasis. Fine tuning of the LADAR picture is still needed to display small obstacles in false color."

"LADAR imagery and symbology sets were very impressive and allowed a better level of control and situational awareness (during degraded visual conditions) than I have experienced before. The workload to fly an approach into brownout and successfully land is very high. In my opinion, I would want to see some changes in symbology before I would recommend this for employment by an "average" pilot to execute DVE [degraded visual environment] approaches to a spot." (Meaning a point whose coordinate was not entered into the guidance system)."

"Recommend the approach profile be modified to more closely reflect current Navy tac-no hover profile, for increased controllability, decreased power requirements, decreased aircraft wear (reduction of time in full brownout). Recommend symbology set 8 [single] be modified with the above profile, and the flight path marker and 'speed worm' be removed. In my opinion, this would be the best symbology set."

"Observation: Flying a precise heads-down approach AND crosschecking the landing zone may be an excessive workload for a single pilot.
Recommendation: Assess options to divide imagery analysis (e.g. obstacle detection and landing point selection) and aircraft control between two pilots."

"Observation: It is difficult to crosscheck altitude cues (AGL and VSI) during the terminal phase of the approach.
Recommendations:
1) Add an intuitive reference to the aircraft symbol to give some perspective of height above touchdown when below 10'
2) Add radar altitude digits next to the aircraft symbol when below 40 kts.
3) Move VSI cue next to the aircraft symbol."

"Observation: The most difficult aircraft control occurs at very low speed (<3 kts) and low altitude (<20'). This is also when you lose the "cup" velocity target.
Recommendation: As the recommended velocity approaches 3 kts, move and anchor the cup at 3 kts straight forward (regardless of desired landing point location). Hold the forward/3 kt cue until touchdown."

Most pilots commented in the debriefing that swirling dust in the FLIR display created a relative motion illusion giving the pilot an incorrect cue of movement.

Hover Maneuver Comments

"Overall, I think this Burns LADAR sensor coupled with the BOSS symbology (when both are optimized for a particular aircraft, service, and mission), has the potential to decrease the risk for dust external load operations as done in theatre today, and allow an expanded operational capability at the same risk level current in theatre."

"The workload in flying the approach and maintaining hover position via symbology does not allow the PAC [pilot At Controls] to be actively scanning the imagery and looking for obstacles. A likely better technique would be to have the PNAC [Pilot Not At Controls] scanning the imagery for obstacles in and around the load, while the PAC focused on flying the aircraft. Good CRM [Crew Resource Management] between the front and the back of the aircraft would likely still be very necessary, using current crew chief calls/direction in addition to imagery and symbology in and around the load to ensure a successful pickup."

"The hover position indicator at the 250 ft scale was very sensitive (on all approaches of the day). Good position maintenance is possible at the expense of extremely high pilot workload. No spare capacity."

Conclusions

1) The combination of the 3D-LZ LADAR and BOSS symbology set enabled safe brownout landings on 77% of the attempts. Safe go-around maneuvers were demonstrated by the evaluation pilot on the remaining 23% of the attempted landings. Five out of the eight go-around maneuvers were called for by the safety pilot. Pilots rated the Handling Qualities as Level 2.

For the combination of the 3D-LZ LADAR and BOSS symbology, the following parameters with within desired limits on average: vertical speed < 150 ft/min, forward speed < 5 knots, aft speed < 0.5 knots, and lateral position < 50 ft. The lateral speed was on average in the adequate range. The worst case lateral speed was 1.16 knots (desired < 0.5 knots, adequate <1.0 knots). Longitudinal position was on average within desired for the dual display (< 50 ft) and within adequate with the switched display (< 100 ft).

2.) The approach to hover and hover over load maneuvers were repeatedly accomplished. The hover position was maintained within desired performance (< 2 ft) 5 of 11 times, and within adequate performance (< 5 ft) also 5 of 11 times. For altitude, desired performance (+/-3 ft) was accomplished three times, adequate performance (+/-5 ft) was accomplished four times, and outside adequate performance (>5 ft) was recorded four times.

3) Workload was rated and debriefed as very high for both the landing and hover maneuvers. Pilots said that they did not have the capacity to look for obstacles near the touchdown event, or while in a hover near the load.

4) As expected, there was generally little difference in pilot performance, HQR ratings, and TLX ratings between symbol sets; they were all variants of the BOSS symbol set. The only large difference was that the average longitudinal position error for the dual display condition was 1/3 that of the switched and single displays conditions.

5) Pilots said that the swirling dust clouds in the FLIR image created a relative motion illusion giving the pilot an incorrect cue of movement. In contrast, the LADAR image remained stable and clear of false returns throughout the landing and hover maneuvers. Pilots saw the location of obstacles throughout the landing maneuvers.

Future Suggested Improvements

A possible method to reduce workload is to split the obstacle detection task and the flying task split between the two pilots. The pilot on the controls would use symbology to fly the aircraft, while the pilot not on the controls could concentrate on searching for obstacles. Whether the pilot on the controls should use a head-mounted display is an area of future research; swirling dust clouds seen out the window could create a false sense of motion.

ADS-33 suggests that handling qualities could improve by augmenting the flight control system from a rate-command direction-hold to an attitude-command attitude-hold system. Hover position hold and altitude hold features could also make the hover task more precise and reduce workload.

Precise altitude control in a hover was particularly difficult with the EH-60L flight control system. In addition to improved flight controls in the vertical axis, the scaling on the altimeter may need to be increased, and prediction may need to be added to the vertical speed indicator.

Pilots suggested moving the altitude and vertical speed information closer to the center of the screen. One pilot suggested keeping the speed guidance on all the time during the approach, and to lock the symbol at 3 knots along the aircraft centerline at ground speeds slower than 3 knots.

Small obstacles were displayed as small objects on the screen. They were difficult to see, particularly in a cluttered field. Real-time processing of the LADAR imagery and visual enhancement of the representation of obstacles would aid the pilot in avoiding small obstacles. Reference the companion paper (Ref. 1).

Pilots suggested modifying the horizontal speed guidance algorithm to reduce the time in the brownout. This work is currently being conducted at AFDD in simulation.

One pilot noted that the system should be expanded to provide horizontal speed guidance and vertical descent rate guidance for situations where there is no pre-stored landing point coordinate.

In the future two types of landings should be tested. In one case the pilots should try to land with some forward speed, and in this case the longitudinal position boundary should be larger than the lateral boundary. In another case pilots should try to land with zero forward speed, with equal longitudinal and lateral position boundaries.

Video instrumentation of the distance between the ground and the wheels would aid in post-flight analysis of data.

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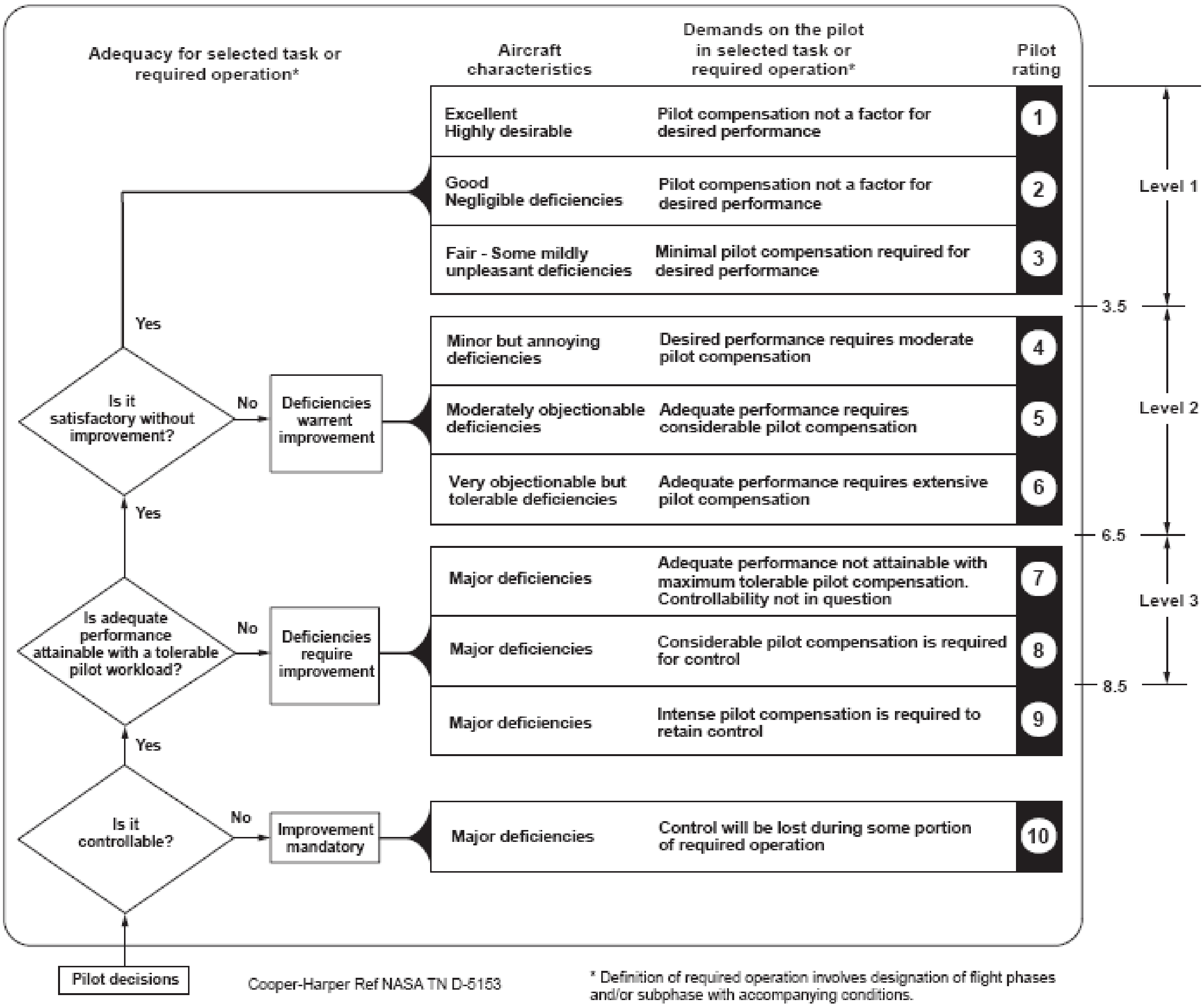
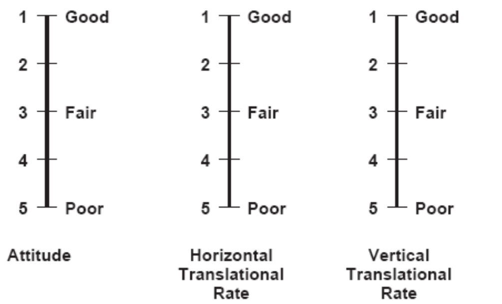
Appendix A
Cooper-Harper Handling Quality Rating Scale and Visual Cue Rating



Cooper-Harper Ref NASA TN D-5153

* Definition of required operation involves designation of flight phases and/or subphase with accompanying conditions.



Pitch, roll and yaw attitude, and lateral-longitudinal, and vertical translational rates shall be evaluated for stabilization effectiveness according to the following definitions:

Good : Can make aggressive and precise corrections with confidence and precision is good.

Fair : Can make limited corrections with confidence and precision is only fair.

Poor: Only small and gentle corrections are possible, and consistent precision is not attainable.

Ref. 21: ADS-33E-PRF 1996.