# Annex C – COMBINATION OF VISUAL DISPLAY SYSTEM WITH SENSOR TECHNOLOGIES

## C.1 3D-LZ LADAR SYSTEM

In response to a request from the Air Force Special Operations Commander in developing and fielding a solution (November 2005), the Air Force Research Laboratory (AFRL) began a program to develop a high-performance imaging LADAR (Laser Radar) system capable of rendering high-resolution images of the landing site prior to brownout landings. This program was entitled "3D-LZ". AFRL selected the H.N. Burns Engineering Corporation to develop the first 3D-LZ prototype based on their Eye-safe Burns Engineering Active Infra-Red (EBAIR) sensor currently in use for commercial precision surveying applications. The LADAR sensor package weighed 100 lbs (not including the aircraft mount) and included a self-contained Applanix POS AV 510 inertial navigation system with a Honeywell LN200 gyro to geo-reference the laser returns (Figure C-1). A GPS/GLONASS receiver and inertial processor were included in the LADAR Graphics Generator located in the aircraft cabin. The GPS receiver was connected to an antenna mounted to the upper surface of the aircraft tail (outside of the main rotor disc). The LADAR was set for a maximum range of 2,000 ft. The sensor had a 60 degree horizontal field of view and was vertically gimballed to allow for a variable vertical field of view of up to 120 degrees. For brownout landing testing, the vertical field-of-view was set from the aircraft waterline to 30 degrees below the aircraft waterline, while for external load operations the field-of-view was set from 5 degrees above to 55 degrees below the waterline. With a 30 degree vertical field-of-view, the LADAR required approximately 3.3 seconds to complete a full scan. The system used an H. N. Burns Engineering Corporation proprietary technique for determining whether LADAR returns were hard-target returns or returns from blowing sand and then passed only hard-target return information into the dynamic navigation database. The dynamic database maintained two million data points and purged older data only when required to make room for newer data. Therefore, in heavy dust conditions where almost no hard-target LADAR data was being added to the database, the database retained the LADAR information gathered prior to entering the dust. Due to the dust rejection algorithm, there was no need to turn off the LADAR to prevent contamination of the database by dust returns. The LADAR continued to sample throughout all segments of the flight to include approach, landing and take-off. Additional technical detail on the 3D-LZ Prototype I LADAR is provided in an International Society for Optical Engineering paper.

**Figure C-1: Gimballed LADAR, Fixed FLIR, and Fixed Color Camera Mounted on Aircraft Nose.**

The 3D-LZ system incorporated two 6 x 8 inch, 1024 x 768 resolution, sunlight readable, LCD cockpit displays to present the sensor imagery to the pilot. These color displays were mounted in the portrait format. Tests were conducted using both LADAR and FLIR sensors for the background imagery. LADAR imagery was tested in three possible modes: true color, false color and hybrid color. In true color mode, the LADAR image pixels were colored using data from a digital camera mounted in the LADAR sensor housing. This mode was only usable when there was adequate ambient light for operation of the digital camera. False color mode colored the LADAR image based on the elevation of each point relative to the elevation of the intended landing point. The raw LADAR returns were geo-referenced in real time and stored in the dynamic navigation database with latitude, longitude and elevation. The elevation of the intended landing point was estimated in real time based upon LADAR terrain height measurements. This elevation value was updated several times during the approach to fine-tune the coloration of the image closer to touchdown. Although a number of color schemes were used, the final false color configuration used green, amber and red in order of ascending elevation. Green was used from the landing point elevation to 18 inches, amber was used from 18 inches to 6 feet, and red was used above 6 feet to indicate those obstacles which represented a potential rotor strike hazard. Shades of blue were used for elevations below the intended landing point. The hybrid color mode was intended to show the landing zone in true color with obstacles shown in false color. The hybrid mode used the same elevation color coding as the false color mode with the exception of using true color in place of green. Examples of all three modes are shown in Figure C-2 with a day-TV image of the scene for comparison. During the flight test the LADAR was set to function in true color for enroute flying (more than 0.25 nautical miles from the landing point), with a change to either false color or hybrid color when closer than 0.25 nautical miles from the intended landing point.

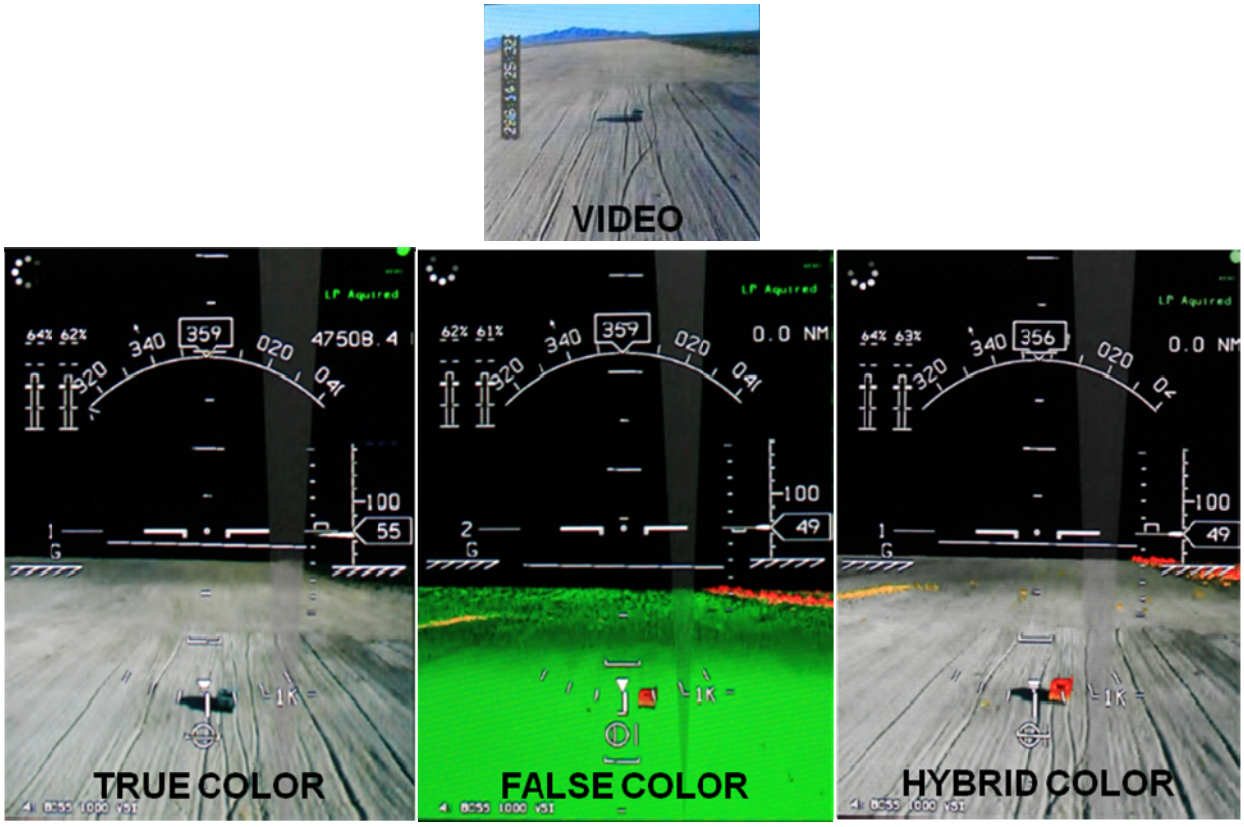


**Figure C-2: LADAR Display Modes.**

### C.1.1 Integration of Symbology and Sensor-Based Imagery

*AFDD SV Simulator.* After the flight test at NRC, the BOSS symbology was selected as a candidate symbol sets for the 3D-LZ program. The HH-60 Block Change Order BCO005 symbology was selected as the baseline set for comparison. 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 display. 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 (Figure C-3, [1]). 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 [2].

**Figure C-3: AFDD Synthetic Vision Cab.**

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 (Figure C-4). A LADAR simulation was added, which used pre-sampled LADAR data from the Yuma test site. A large dome projection system (160° horizontal x 80° vertical FOV) was used, with improved brownout visualization, and a high resolution terrain database that modelled three landing sites located at Yuma Proving Grounds, AZ. The helicopter model was upgraded to the high fidelity GENHEL model [3].

**Figure C-4: AFRL SIRE Helicopter Simulator.**

The experiment utilized a 2 x 2 x 2 within-subjects, repeated measures full factorial design. The first factor was sensor type with two levels: LADAR and Forward-Looking Infrared (FLIR). The second factor was symbology type with two levels: HH-60G Block Change Order 5 and BOSS. Finally, the third factor was approach type: direct and offset (where the landing point needed to be moved). A total of eleven US military trained helicopter pilots completed the simulation. All training and data collection was performed at the Synthetic Immersive Research Environment (SIRE) HH-60 helicopter simulator located at Wright-Patterson AFB, OH. The simulator includes a 40-ft diameter dome out-the-window visual display (160° horizontal x 80° vertical FOV) with a simulated HH-60 cab. The visual database modelled three landing sites located at Yuma Proving Grounds, AZ. The GenHel model developed by NASA and the US Army was employed as the flight model.

Distance between the intended and actual landing points were significantly lower with the BOSS symbology (38 ft) when compared to the HH-60G BC005 (55 ft) ($p$ = 0.006). Longitudinal speed at touchdown was significantly lower for the BOSS symbology (1.5 ft/sec) when compared to the HH-60G (2.7 ft/sec) ($p$ = 0.000). The BOSS symbology also produced a significantly lower HQR (4.18) when compared to the HH-60G (5.08) ($p$ = 0.010). See Figure C-5,Figure C-6 and Figure C-7.

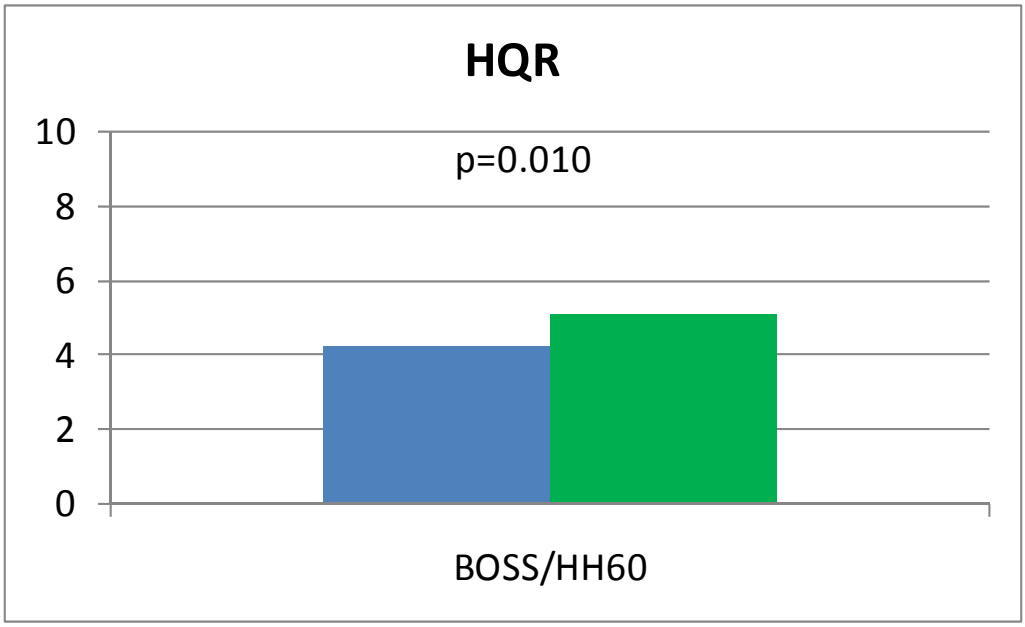


**Figure C-5: Average Handling Quality Rating.**

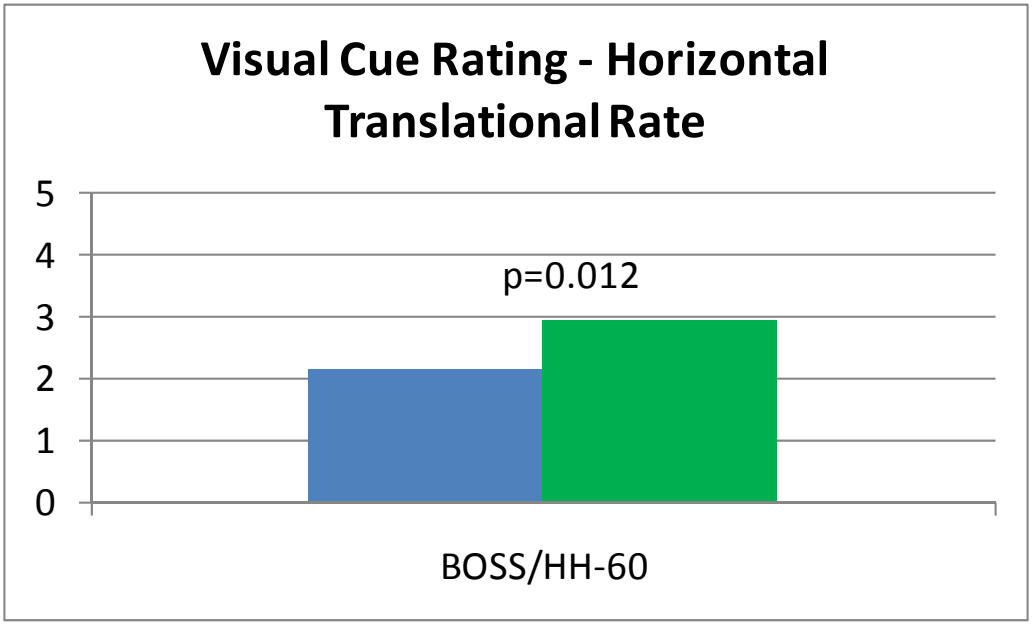


**Figure C-6: Average Horizontal Translation Rate Rating.**

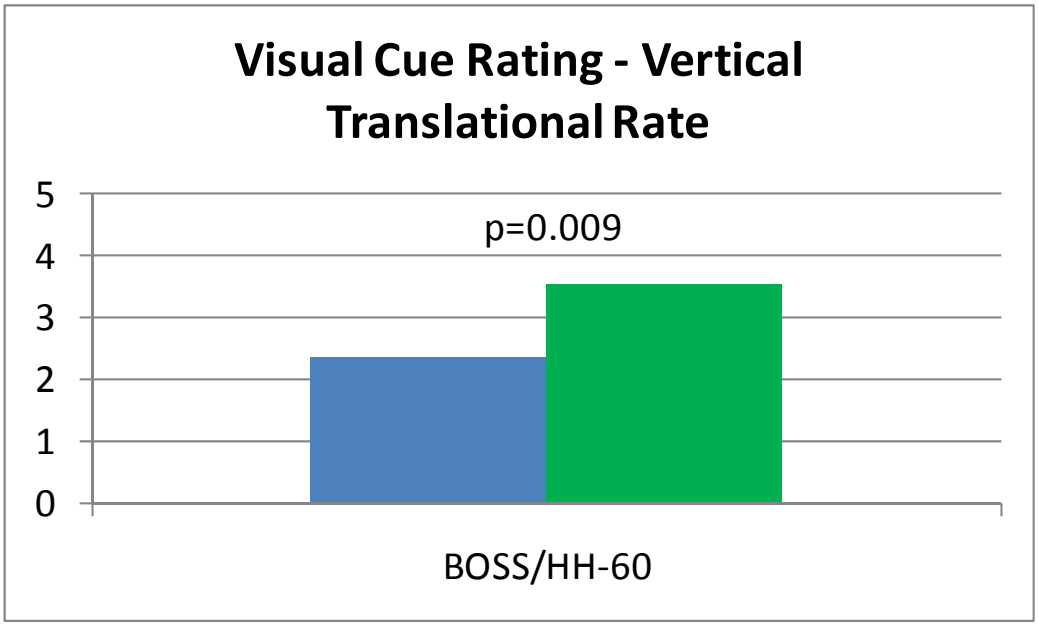


**Figure C-7: Average Vertical Translation Rate Rating.**

HQR 4: Minor but annoying deficiencies. Desired performance requires moderate pilot compensation.

HQR 5: Moderately objectionable deficiencies. Adequate performance requires considerable pilot compensation.

Horizontal rate Visual Cue Ratings (VCR) were significantly lower for the BOSS symbology and LADAR when compared to the HH-60G symbology ($p$ = 0.012). Likewise, vertical VCRs were significantly lower with the BOSS symbology ($p$ = 0.009).

Within the NASA TLX workload assessment, mental load was significantly lower for the BOSS symbology when compared to the HH-60G and also for the direct approach ($p$ = 0.012) when compared to offset ($p$ = 0.003). Physical demand, temporal demand, effort, performance, and frustration were all significantly lower with the BOSS symbology when compared to the HH-60G ($p$ <0.05). Subjectively, pilots felt the BOSS symbology had less clutter, a preferred pitch ladder, and better performance than the HH-60G. In addition, the pilots preferred the LADAR sensor to the FLIR for brownout landings and landing zone assessment. 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. See Figure C-8.

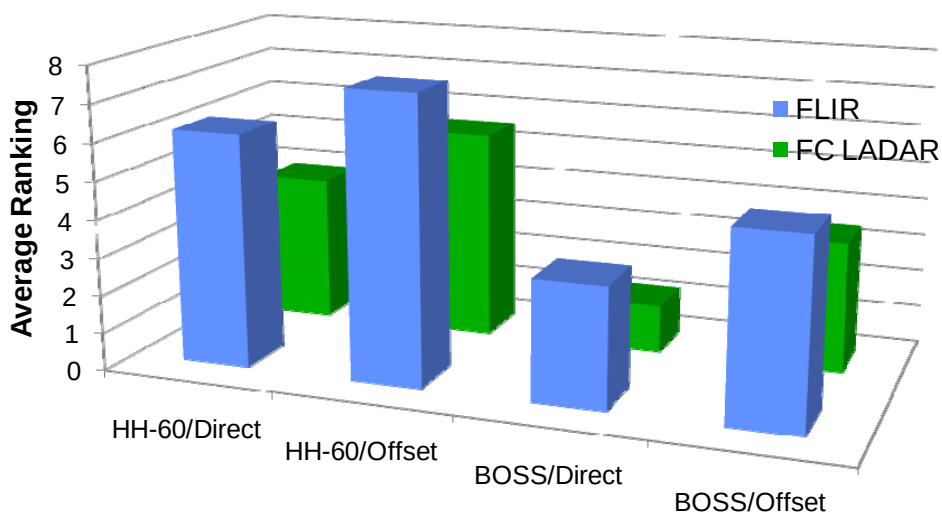


**Figure C-8: Average Preference Ranking.**

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.

### C.1.2 3D-LZ Yuma Flight Test

The US Army EH-60L Black Hawk aircraft Serial Number 87-24657 was modified to install the H.N. Burns Engineering 3D-LZ LADAR. To make the LADAR imagery visible during approach and landing, it was necessary to change the scale of the image as the aircraft approached the landing point. As a result, it was also necessary to change the symbology to scale with the background imagery. 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 C-9 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.

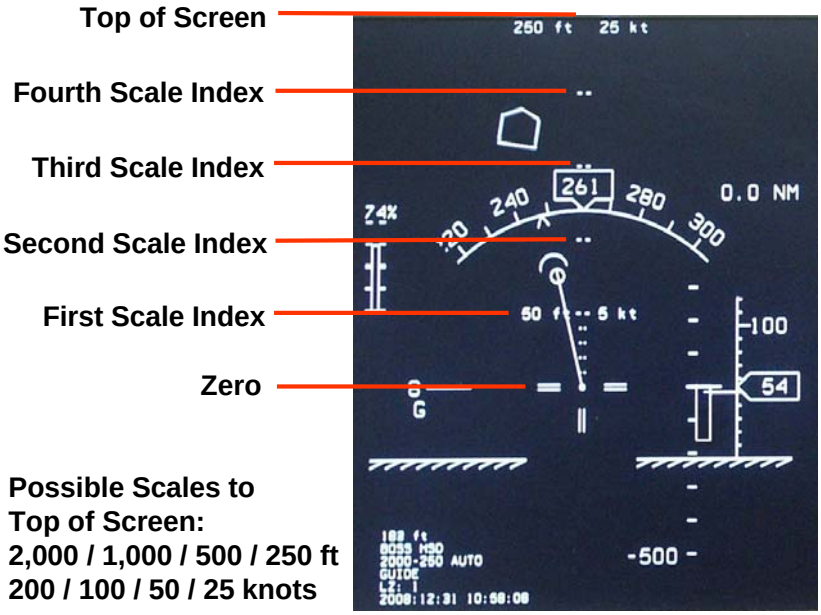


**Figure C-9: Scales for the Horizontal Velocity, Target Velocity, and Target Position Symbols.**

Figure C-10 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.

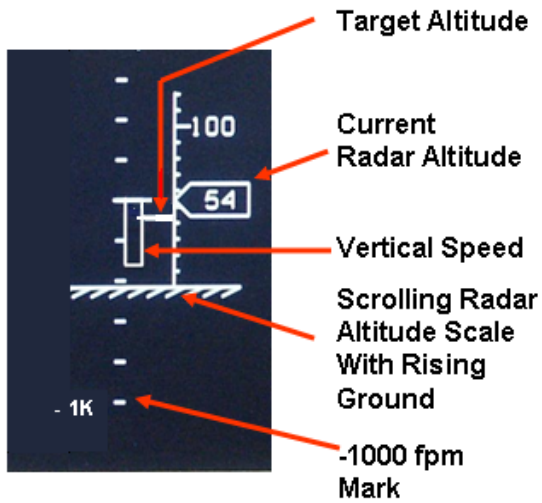


**Figure C-10: Combined Altimeter and Vertical Speed Indicator with Target Altitude Symbol Used for the Approach to High Hover Maneuver.**

Figure C-11 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 Figure C-12. 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.

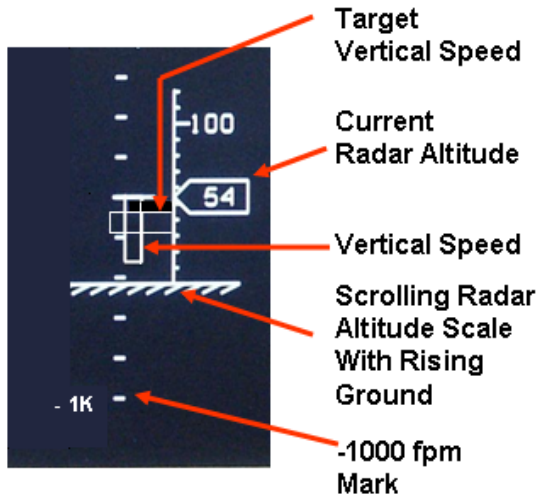


**Figure C-11: Combined Altimeter and Vertical Speed Indicator with Target Vertical Speed Symbol Used for the Landing Maneuver.**

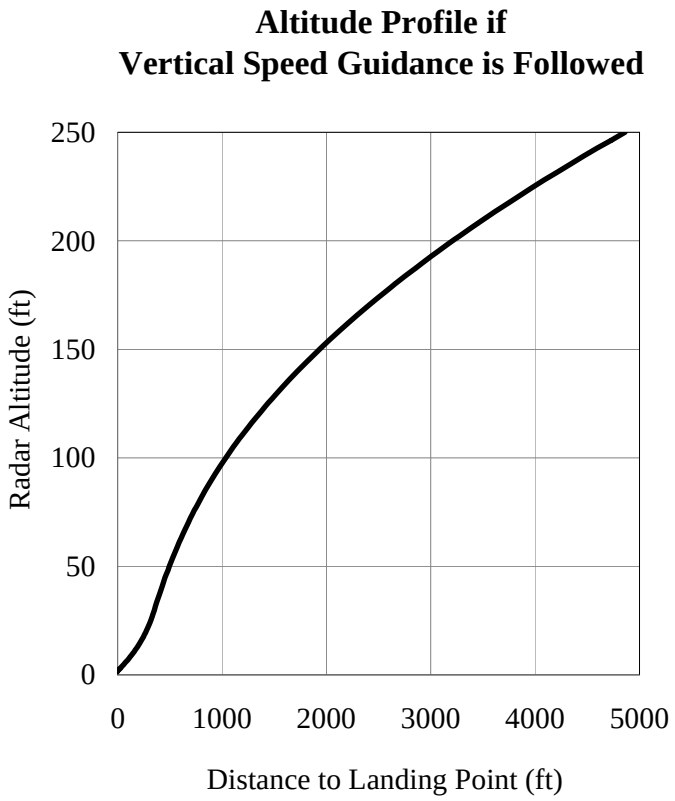


**Figure C-12: Vertical Profile for the Vertical Speed Guidance Algorithm.**

A total of three display configurations were evaluated in the flight test. One of the three symbol sets is called "dual" in this annex and is comprised of a VSD with forward-view terrain imagery, and a HSD with downward-view terrain imagery as shown in Figure C-13. 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.

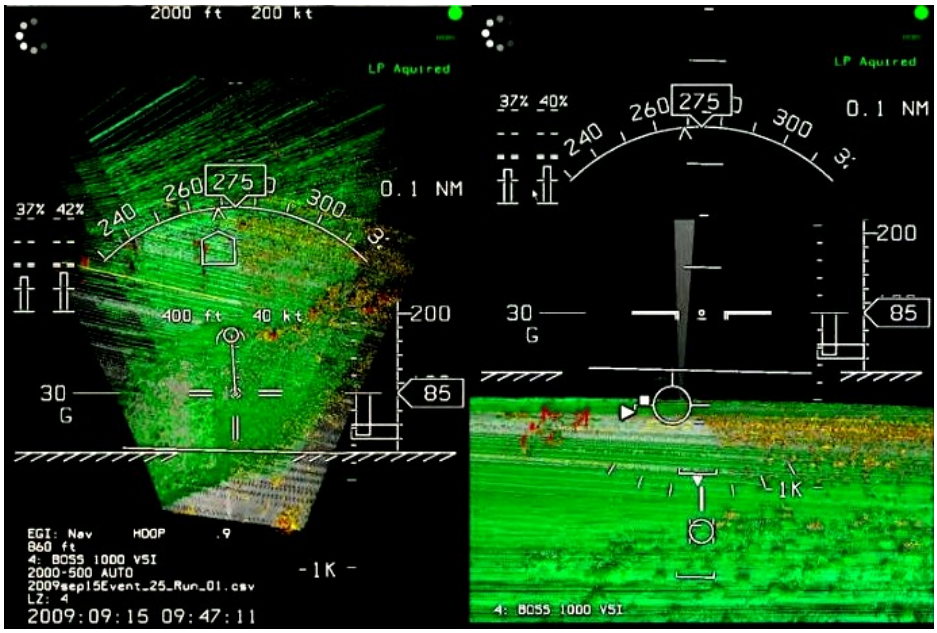


**Figure C-13: Dual Display with VSD (Right) and HSD (Left).**

The second of the three symbol sets was developed by AFRL and is called "switched" in this paper (Figure C-14). 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.

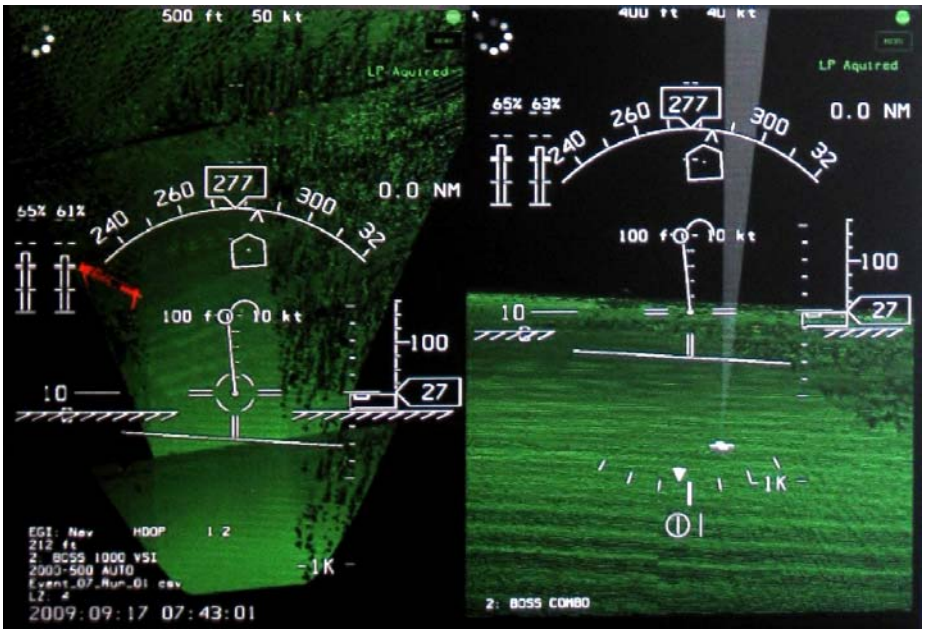


**Figure C-14: Right: Switched Display on Low-Speed Page; Left: Display Stays as an HSD.**

The third variant of the BOSS symbol set was 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.

Landings at the YPG test site were all performed at prepared sites. All but three landings were conducted at the Oasis site, shown in Figure C-15, 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 (Figure C-16).

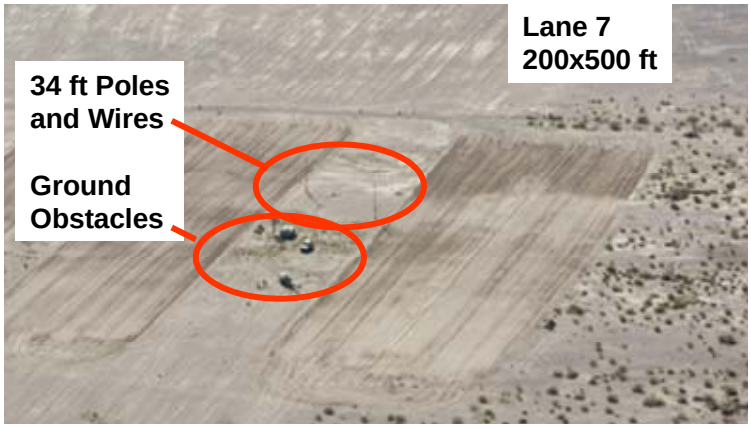


**Figure C-15: Landings were Conducted Primarily in Lane 7 at the Yuma Proving Ground Dust Course.**

**Figure C-16: Lanes were Plowed to Increase Quantity of Dust (EH-60L shown).**

Landing maneuvers were started at 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 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.

#### C.1.2.1 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.

Figure C-17 through Figure C-23 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 C-17 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 Figure C-17, 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 Figure C-17.

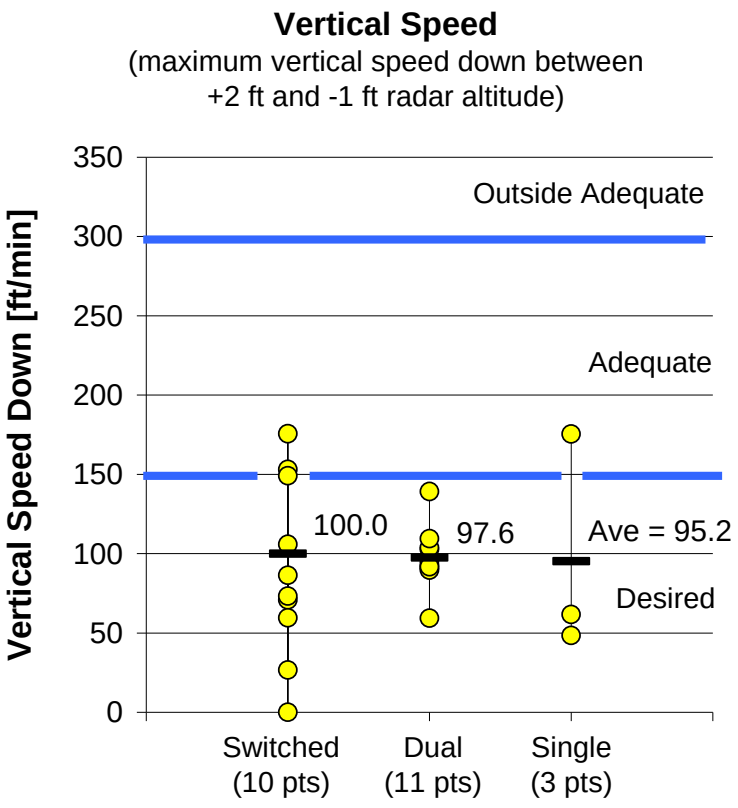


**Figure C-17: Vertical Speed.**

Figure C-18 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.

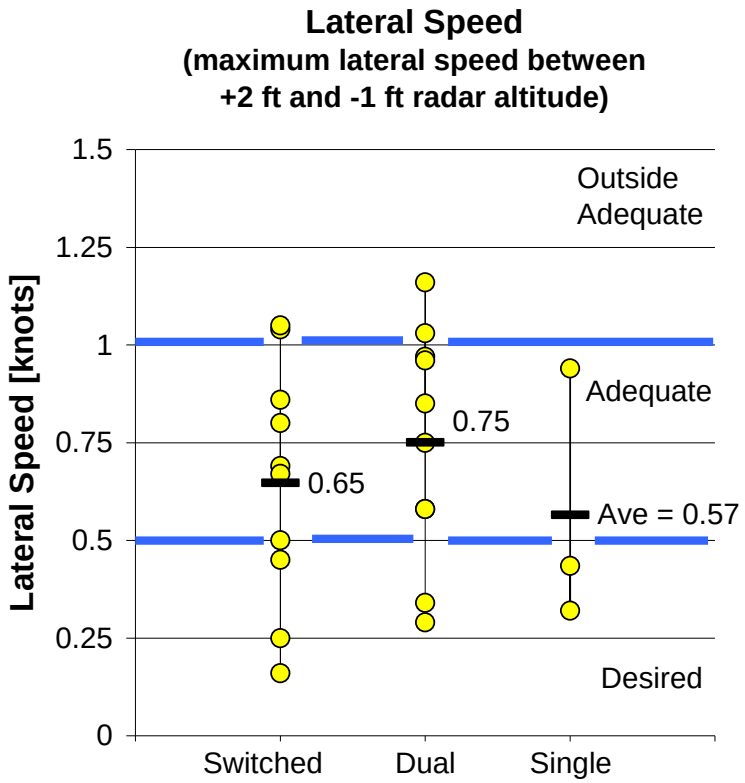


**Figure C-18: Lateral Speed.**

Figure C-19 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.

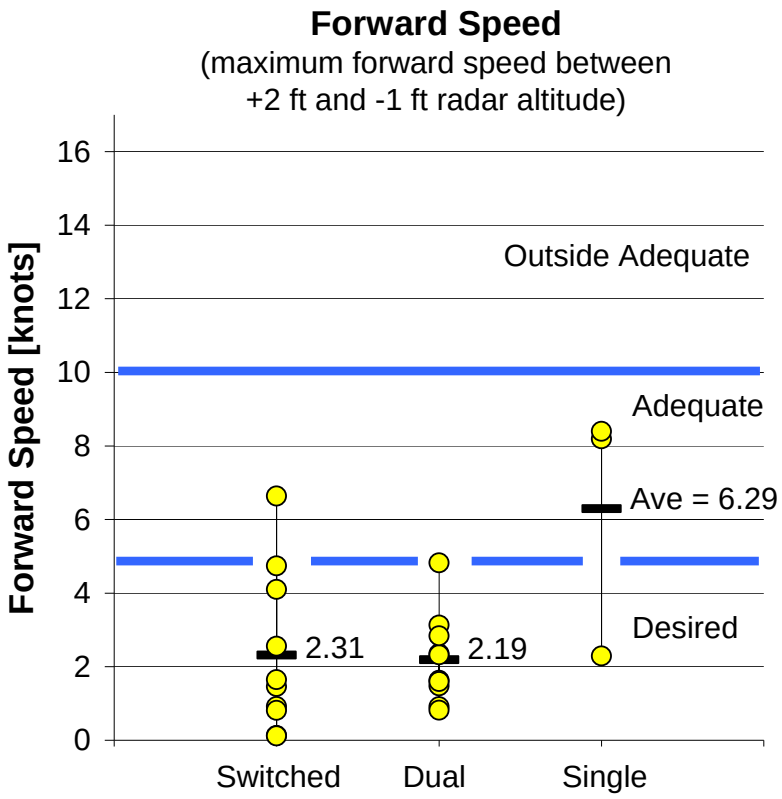


**Figure C-19: Forward Speed.**

Figure C-20 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.

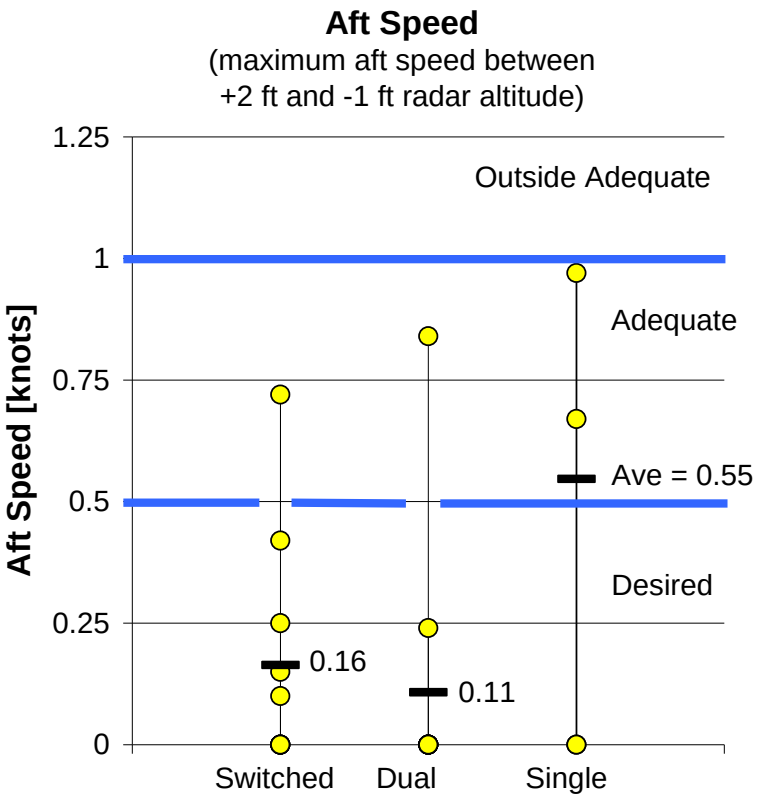


**Figure C-20: Aft Speed.**

Figure C-21 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 do include data from the alternate site.

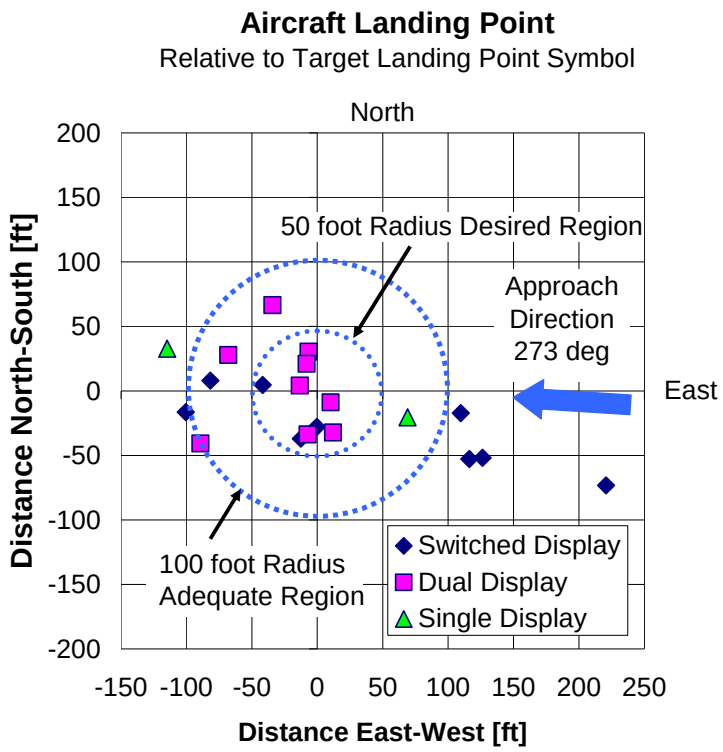


**Figure C-21: Landing Position (at -1 ft Radar Altitude) Relative to Target Landing Point as Measured by EGI and Displayed to the Pilot.**

Figure C-22 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.

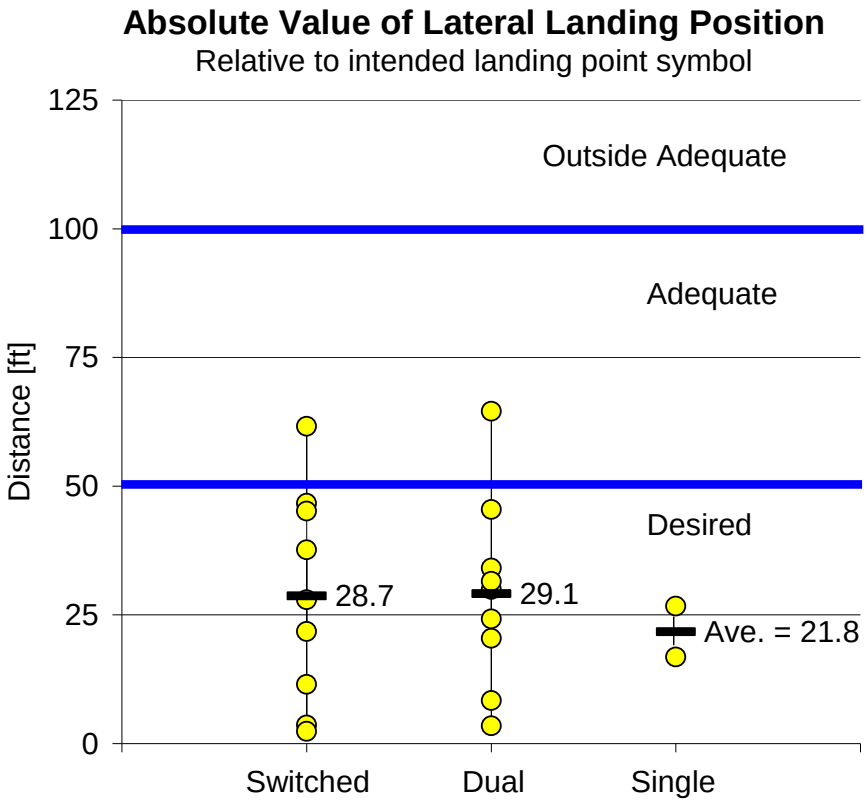


**Figure C-22: Lateral Position Error.**

Figure C-23 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.

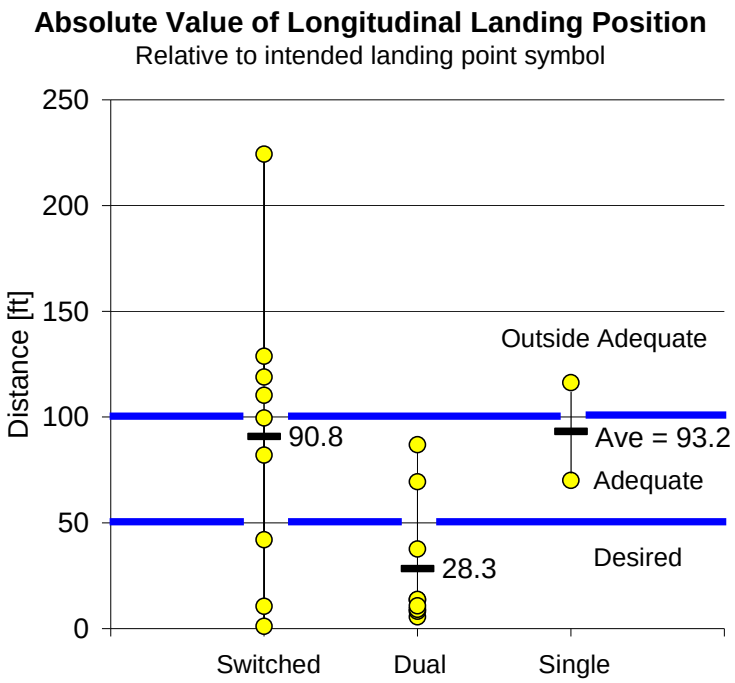


**Figure C-23: Longitudinal Position Error.**

### C.1.2.2 Subjective Results

Figure C-24 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.

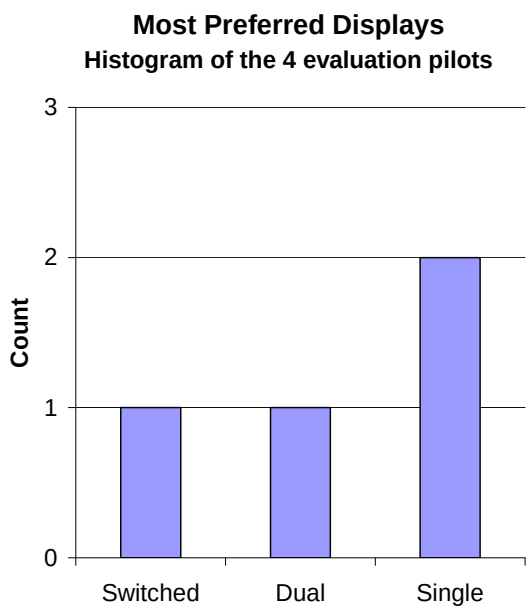


**Figure C-24: Display Preference for the Four Evaluation Pilots.**

Figure C-25 shows the average HQR ratings for the three displays, which ranged between a rating of 4.3 (dual display) and 5.5 (single display). 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 Figure C-25 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.

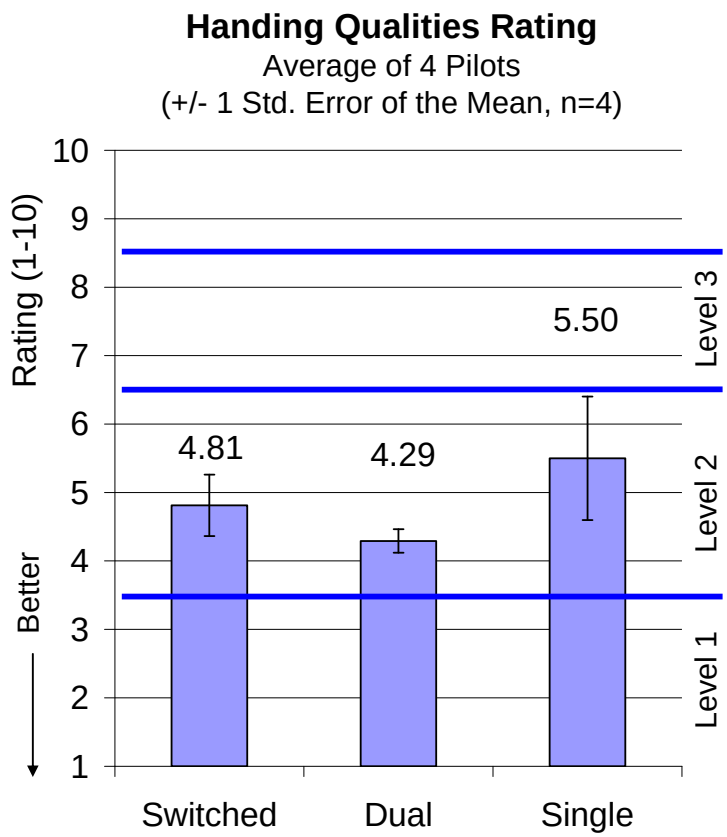


**Figure C-25: Average HQR.**

HQR 4: Minor but annoying deficiencies. Desired performance requires moderate pilot compensation.

HQR 5: Moderately objectionable deficiencies. Adequate performance requires considerable pilot compensation.

Figure C-26 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, the scores in Figure C-26 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.

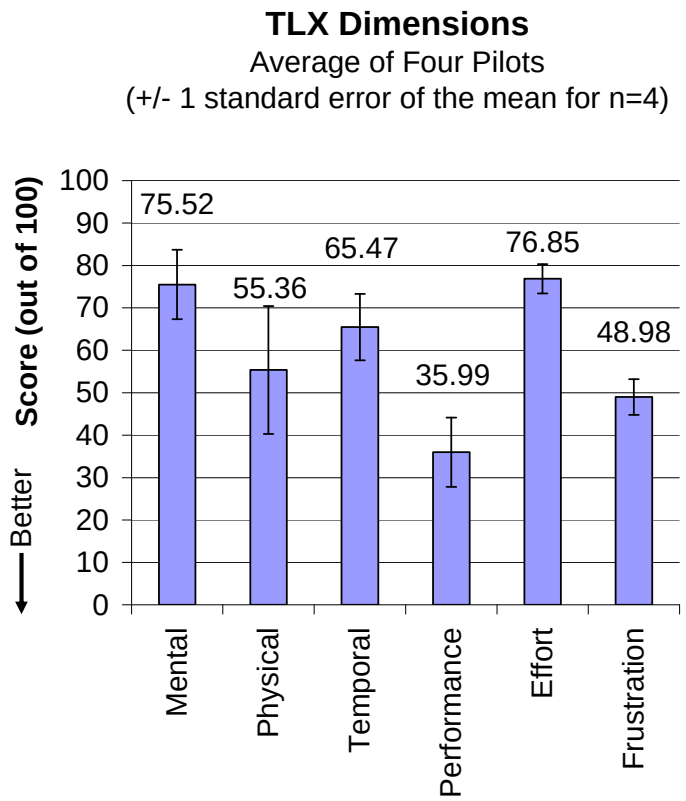


**Figure C-26: Average Scores for the TLX Dimensions.**

Specific quotations from the pilots are provided below:

> "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 head-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.

#### C.1.2.3 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.

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).

3) Workload was rated and debriefed as very high for the landing maneuver. 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.

#### C.1.2.4 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. If the pilot-on-the-controls had a head-mounted display with symbology, then that pilot could keep looking out the window, while the pilot-not-on-the-controls could concentrate on searching for obstacles from the sensor imagery on the panel-mounted displays.

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 it at 3 knots along the aircraft centerline direction at 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.

## C.2 REFERENCES

[1] Szoboszlay, Z., Jennings, S. and Carignan, S., Results and Comments for the Loon Symbology Study (2009), National Research Council of Canada Flight Test Report, FTR-FRL-2009-0024.

[2] Whalley, M. (1994). Effects of Longitudinal and Normal Load Factor Envelopes on Combat Helicopter Handling Qualities, NASA TM 4558.

[3] Ballin, M. (1987). Validation of a Real-Time Engineering Simulation of the UH-60A Helicopter, NASA TM-88360.