MOTION-BASE SIMULATOR EVALUATION OF AN AIRCRAFT USING AN EXTERNAL VISION SYSTEM

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Abstract

Twelve air transport-rated pilots participated as subjects in a motion-base simulation experiment to evaluate the use of eXternal Vision Systems (XVS) as enabling technologies for future supersonic aircraft without forward facing windows. Three head-up flight display concepts were evaluated –a monochromatic, collimated Head-up Display (HUD) and a color, non-collimated XVS display with a field-of-view (FOV) equal to and also, one significantly larger than the collimated HUD. Approach, landing, departure, and surface operations were conducted. Additionally, the apparent angle-of-attack (AOA) was varied (high/low) to investigate the vertical field-of-view display requirements and peripheral, side window visibility was experimentally varied. The data showed that lateral approach tracking performance and lateral landing position were excellent regardless of AOA, display FOV, display collimation or whether peripheral cues were present. However, the data showed glide slope approach tracking appears to be affected by display size (*i.e.*, FOV) and collimation. The monochrome, collimated HUD and color, uncollimated XVS with Full FOV display had (statistically equivalent) glide path performance improvements over the XVS with HUD FOV display. Approach path performance results indicated that collimation may not be a requirement for an XVS display if the XVS display is large enough and employs color. Subjective assessments of mental workload and situation awareness also indicated that an uncollimated XVS display may be feasible. Motion cueing appears to have improved localizer tracking and touchdown sink rate across all displays.

Introduction

NASA is conducting research into technologies for reducing the impact of aircraft sonic boom on people and the environment. The primary objective of this research is to enable regulatory changes that would permit unrestricted supersonic flight overland, both domestically and internationally. A successful low-boom design drives the shaping and configuration of the vehicle. One such conceptual configuration is shown in Figure 1. As evident in this figure, the forward visibility for the pilot/flight crew is severely compromised as a result of the vehicle shaping.

Under the Fundamental Aeronautics (FA) Program, Supersonics project, NASA is performing fundamental research, development, test and evaluation of flight deck and related technologies to support these low-boom, supersonic configurations by use of an eXternal Vision System (XVS). XVS is a combination of sensor and display technologies intended to provide an equivalent level of safety and performance to that provided by forward-facing windows in today's aircraft.

Figure 1. Conceptual Low-Boom Supersonic Aircraft Configuration

Without XVS, the economic viability of a low-boom supersonic aircraft is questionable, since the lack of forward visibility by the pilot would severely restrict aircraft operations and airspace usage especially when the weather is clear and visibility conditions are unrestricted – *i.e.,* without an XVS, a low-boom supersonic aircraft cannot operate under Visual Flight Rules (VFR) since it can't "see-and-avoid" and "see-to-follow."

"Sense-and-avoid" technologies, in lieu of see-and-avoid, are actively being pursued in the Uninhabited Air Vehicle (UAV) sector and their work is directly applicable [1]. To date, however, these concepts are immature and will unlikely be advanced enough to support the operating concepts and airspace needs of a commercial business aircraft [2].

Acceptance of these technologies by owners and operators of commercial and business aircraft is also debatable.

Significant research was conducted under NASA's High Speed Research program during the 1990s on the design and development issues associated with an XVS for a conceptual high-speed civil transport aircraft [3,4]. What emerged from this research (and still holds true today) is that the key challenge for an XVS design exists during VFR operations. The driving XVS design standards emerged from the three tenets of VFR operations which are "see-and-avoid," "see-to-follow," and "self-navigation." These VFR-type requirements are not unique to low-boom supersonic aircraft but the absence of natural forward vision creates the equivalent performance and safety requirements for an XVS design [2].

An experiment was conducted to evaluate some of the design requirements of an XVS - without the need for forward-facing windows - and to determine the interaction of XVS and peripheral vision cues for terminal area and surface operations. Another key element of the testing investigated the pilot's awareness and reaction to non-normal events (*i.e.,* failure conditions) that were unexpectedly introduced into the experiment. These non-normals are critical determinants in the underlying safety of all-weather operations.

This paper describes an experimental evaluation of field-of-view (FOV), collimation, and peripheral cues on pilot performance and subjective ratings of situation awareness and workload during terminal area operations. In addition, motion effects are analyzed by comparing objective results from this motion-base simulation experiment to a previously conducted experiment [8] that manipulated the same independent variables using the same simulator in fixed-base mode. The subject pilots were different although the recruiting criteria were the same. Further, the objective data from this test are being used to develop performance-based approach and landing standards which might establish a basis for future all-weather landing certification.

Method

Subjects

Twelve pilots, representing 8 airlines participated in the experiment. All participants had previous experience flying Head-Up Displays (HUDs). The subjects had an average of 1173 hours of HUD flying experience and an average of 16.8 years and 13.3 years of commercial and military flying experience, respectively.

Simulation Facility

The experiment was conducted in the Integration Flight Deck (IFD) simulator (Figure 2) on the motion-base platform using the Cockpit Motion Facility (CMF) at NASA Langley Research Center. The IFD emulates a Boeing B-757-200 aircraft and provides researchers with a full-mission simulator capability. The cab is populated with flight instrumentation and pilot controls, including the overhead subsystem panels, to replicate the B-757 aircraft. The collimated out-the-window (OTW) scene is produced by an Evans and Sutherland Image Generator 4530 graphics system providing approximately 200 degrees horizontal by 40 degrees vertical FOV at 26 pixels per degree. The forward windows were masked for this experiment but the side windows were unblocked to test the effects of peripheral cues (with and without) during approach, landing, taxi, and departure operations.

The evaluation pilot (EP) occupied the left seat, as the Pilot Flying (PF) for this experiment. The left seat included an overhead HUD projection unit and a 22 inch diagonal liquid crystal display (LCD) referred to as the XVS display (Figure 2). The right seat was occupied by a principal investigator (PI) who acted as First Officer during data collection. The PI aided the EP by providing callouts during taxi and performing airplane configuration tasks during departure runs.

Head-Up Display

The HUD was collimated and subtended approximately 26^{o} horizontal by 21^{o} vertical FOV. Note that to maintain conformality with the outside world, the FOV for the HUD imagery was fixed and could not be varied by the EP. The HUD presentation was written strictly in raster format from a video source (RS-343) input. The input consisted of a video mix of symbology and a simulated camera image (i.e., XVS display). The symbology included "haloing" to ensure that the symbology was highlighted against the scene imagery background. Overall HUD brightness and contrast controls were provided to the pilot. In addition, the EP was able to independently adjust the flight symbology brightness relative to the raster imagery. The pilot also had a declutter control, implemented as a four-button castle switch on the left hand horn of the PF yoke. Four "declutter" states were available to the EP: 1) Symbology toggle (on/off); 2) Imagery toggle (on/off); 3) All decluttered (no symbology or imagery); and 4) All displayed (both symbology and imagery).

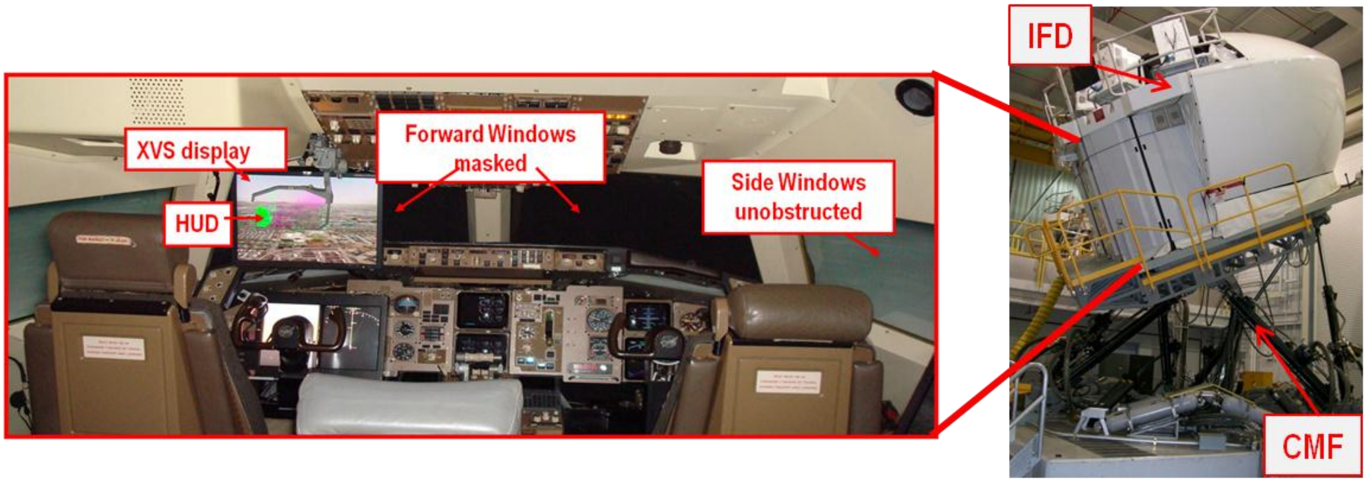


Figure 2. IFD Simulator with HUD, XVS Display (interior view) and CMF with IFD (exterior view)

eXternal Vision System Display

The XVS display subtended approximately 44^{o} horizontal by 34^{o} vertical FOV and was located approximately 19 inches from the pilot design eye point. The imagery on the XVS display was conformal with the OTW view just as the HUD imagery. However, this display differed from the HUD as it was larger, used color, and was not collimated. The XVS display emulated a camera view mounted on the outside of the aircraft with flight symbology overlaid on the scene. Thus, any items (e.g., traffic, approach lighting system, terrain, runway markings, etc.) that would be visible to a real camera system would be visible in the color camera imagery. This photo-realistic camera imagery was unaffected by the outside weather (similar to HUD SV imagery) to parametrically test for any interactions between display size and peripheral cues. The same declutter control described in the HUD section above was utilized with the XVS display.

Symbology

The same symbology set was used for the XVS and HUD concepts (Figure 3). The symbology included pathway guidance and a runway outline. The pathway symbology [9] ended at 500 ft HAT and was replaced by a runway outline and a glideslope reference line. A runway outline symbol (8000 ft x 200 ft) was drawn using the threshold coordinates of the landing runway and the aircraft navigation solution to conformally position the symbol. A glideslope reference line was drawn at a descent angle of 3.1 degrees. Also, radar altitude was shown digitally underneath the flight path marker when below 500 ft above ground level (AGL).

A pitch-roll guidance cue ("ball") used modified pursuit guidance along the desired path [10]. Horizontal and vertical position of the ball reflects the track and vertical flight path angles to fly to the center of the desired path. The path deviation indicators showed angular course deviation (*i.e.*, glideslope and localizer-like) conditions by converting the linear path error data to angle errors and scaling in "dots." Glideslope and localizer raw data indicators which included a deviation scale and angular deviation indication were also provided (*i.e.*, glideslope and localizer deviation).

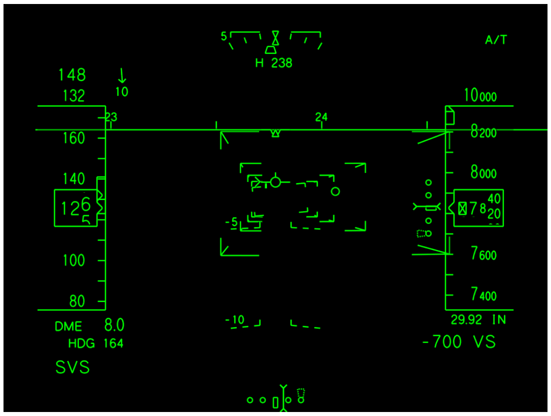


Figure 3. Head-Up Flight Display Symbology Format – Low AOA Condition Shown

Independent Variable – Display Concepts

Four head-up flight display concepts were evaluated by the EPs while flying approaches to Runway 16R at the Reno-Tahoe International Airport (airport identifier RNO). The head-down PFD and ND formats were invariant.

Head-Up Flight Display Concepts

The four head-up flight display concepts (Figure 4 and Table 1) were a partial factorial combination of angle-of-attack, or AOA (low or high) and display type (HUD, XVS display with HUD FOV, or XVS display with Full FOV). Specifically, all three display types were flown in the low AOA condition and only the XVS display with Full FOV was flown in the high AOA condition.

The HUD installed in the RFD simulator uses a pitch bias value of 3 degrees. This means that the waterline (boresight) reference point of the HUD is 3 degrees above the center of the HUD. This bias optimally tailors the placement of the HUD symbology for the B-757 simulator in its nominal operating flight conditions. In Figure 3, the HUD during this "low AOA" condition is shown. With the B757 at approximately 3 degrees in the approach conditions for this test, the flight path marker on short final is approximately at the center of the HUD.

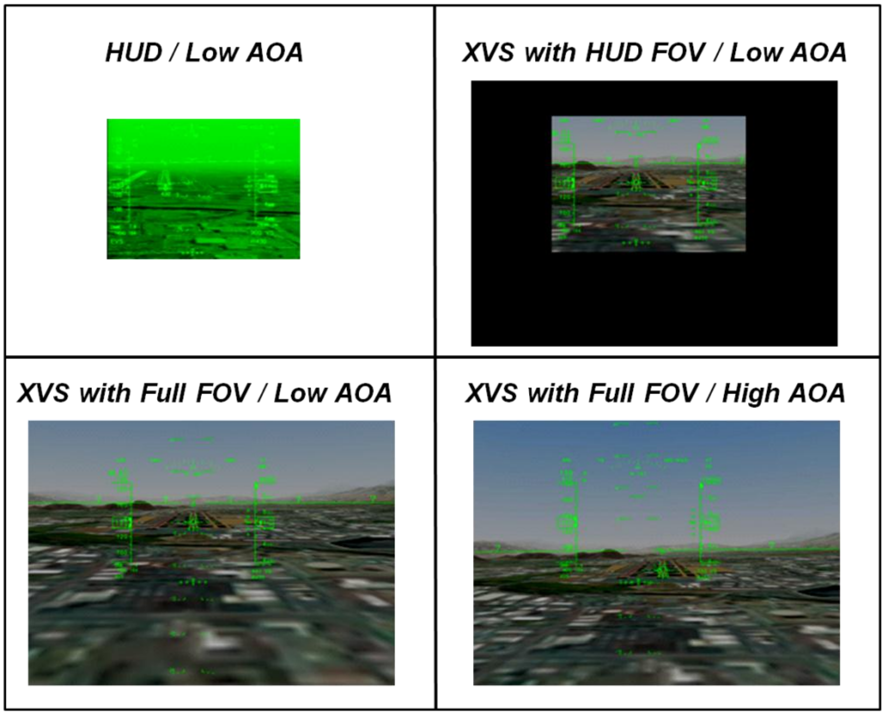
One of the display design issues facing a supersonic aircraft is that they typically operate at high AOA conditions in the approach and landing, due to the high sweep-back wing angles and low camber typically desired for efficient supersonic cruise flight. For the flight deck designer, high AOA conditions on the approach drive the vertical FOV of windows to allow pilot visibility of the approach lights and touchdown zone (see FAA Advisory Circular AC25-773-1 – Reference 11). For the Concorde, a drooped-nose was used to provide this visibility. By analogy, an XVS display, providing equivalent visibility, would require the same vertical FOV, particularly if conformal symbology and imagery create "electronic" visibility. As the AOA becomes very large, the recommended down-angle becomes significantly larger, following the so-called "3-second rule." Review of AC25-773-1 suggests that the substantiation for this requirement is vague and dated, particularly its relevance, as it might be applied to "electronic" visibility systems [2].

As an initial evaluation of this FOV down-angle requirement, a "high AOA" condition was simulated to compare to the "low AOA" condition. To minimize a confound in the experiment, actual high angle-of-attack conditions for the B757 were *not* simulated; otherwise, the flying qualities of the low AOA and high AOA conditions would be radically different. Instead, a pitch bias was introduced.

The high AOA condition used an 8° pitch bias to simulate an increased angle-of-attack to approximate that of a supersonic transport aircraft on approach (Figure 5), approximately 11° angle-of-attack. Comparing Figure 3 and Figure 5 shows the differences in head-up flight display symbology. The pitch bias caused a "symbology cluster" with the flight path marker, guidance cue and localizer deviation scale/marker while the pilots performed an approach on a 3.1 degree glide path to Runway 16R.

The two AOA conditions were evaluated independently on the uncollimated XVS display with the full FOV (44 x 34 degrees) condition. The symbology used in the XVS concepts was identical to that used in the HUD concept.

The XVS and HUD concepts were located in the same head-up positions so the aircraft boresight references for each display were co-located.


HUD / Low AOA

XVS with HUD FOV / Low AOA

XVS with Full FOV / Low AOA

XVS with Full FOV / High AOA

Figure 4. Head-Up Flight Display Concepts

Simulated color camera imagery was mixed with the symbology and shown conformally on the color, uncollimated XVS display for both FOVs. The HUD was stowed to preclude blocking or distortion of the pilot's forward view when using the XVS display. The XVS display was turned off when the EP was evaluating a HUD concept. Note that the forward windows were masked for both display devices and the side windows were unobstructed.

Head-Down Flight Display Concepts

The PFD and ND closely resembled current transport aircraft equipage. However, guidance information was purposely removed from the PFD so that the EPs would focus on the head-up primary flight display concepts. The ND showed the RNO Runway 16R approach path, but it did not include any Enhanced Ground Proximity Warning System or Traffic Alert and Collision Avoidance System information.

Figure 5. Head-Up Flight Display Symbology Format – High AOA Condition Shown

Independent Variable – Peripheral Cues

To test for peripheral cue effects during approach/landing, surface and departure operations, two visibility levels were tested. The peripheral cues were either absent - simulating IMC of 200 ft runway visual range (RVR) - or present - simulating Visual Meteorological Conditions (VMC) of 3 miles visibility.

Independent Variable – Motion Cues

To test for motion cue effects during approach/landing, surface and departure operations, objective measures from this motion-base experiment were compared to a previously conducted XVS fixed-base IFD simulation experiment that manipulated the same independent variables [8].

Evaluation Tasks

Approach

The approach task mimicked an existing visual arrival procedure reflecting an efficient and preferred routing for air traffic control and noise abatement. This approach normally requires visual flight conditions for the crew to see-and-avoid terrain, traffic, and obstacles while navigating with respect to ground references. The approach was a curved, descending path around terrain and obstacles and, thus, tests the ability of the display concepts to support this type of equivalent visual operation. The weather consisted of altitude-based cross winds (wind direction and intensity was dependent on altitude), light turbulence, and varying visibility levels (3 miles or 200 ft RVR). The EP hand-flew the base and final legs of the visual arrival to RNO Runway 16R, using the HUD or XVS display concept with autothrottles engaged, holding 132 knots. The aircraft was configured for landing (landing gear down and flaps 30 degrees) prior to each run, and the aircraft was "cleared to land". The path converged into the instrument landing system approach course, nominally resulting in a stabilized approach no lower than 1,000 ft HAT. For the low AOA runs, the pilot was instructed to follow a pre-briefed taxi clearance requiring the aircraft to exit the runway on a high-speed turnoff onto Taxiway November, turn right on Taxiway Alpha, cross over Runway 7/25, and then turn left on Taxiway Lima where the run ended. For the high AOA runs, the pilot was instructed to come to a full-stop on Runway 16R where the run ended.

Departure

EPs also performed departures flying the RNO "Mustang 7" Departure Procedure. They maintained the runway heading of 168 degrees until waypoint RIJTU (about 5 nmi from the departure runway) and then turned left direct toward the Mustang VORTAC, where the run ended. The weather consisted of altitude-based cross winds (wind direction and intensity was dependent on altitude), light turbulence, and varying visibility levels (3 miles or 200 ft RVR). The EP hand-flew the departure with the HUD, XVS with HUD FOV or XVS with Full FOV display concept and was instructed to climb to 10,000 ft mean sea level (MSL) and 250 knots.

There were up to 3 transport-sized aircraft in the runway environment, but they did not provide any conflicts for the ownship during approach, landing, taxi, or departure operations. There was no Air Traffic Control involvement in the tasks.

Pilot Procedures

Since only pilot-flying evaluations were being conducted, automatic aural altitude call-outs (e.g., 1000, 500, 100 feet, etc.) were included in the simulation to "assist" in altitude awareness. Unlike current FAA regulations, for this experiment, the EP was *not required* to see using natural vision the required landing visual references (as per FAR §91.175) by DA/H (decision altitude/height). The EP was instructed to continue to landing if the required landing visual references were seen in the imagery on the HUD or XVS and if the EP determined that a safe landing could be performed. Otherwise, a missed approach should be executed.

The EPs were instructed to fly the aircraft as if there were passengers aboard, fly the center of the approach path (within ± ½ dot for desired performance and within ± 1 dot for adequate performance), and land as close as possible to the centerline and aim point (1000 feet from the threshold). After landing, they were to capture the center line and then for the low AOA runs only, taxi at a speed with which they were comfortable using the pre-briefed taxi clearance. They were also instructed to initiate a go-around if the landing was not safe or if there were any safety concerns during the approach. EPs were instructed to stop the aircraft if they felt unsafe during surface operations.

Prior to run commencement, the EP was briefed on the type of run to be completed, the display concept to be evaluated, the visibility level, and the wind magnitude and direction.

Experiment Matrix

Nominally, ten training runs and twenty-three experimental runs were completed by each EP. Of the 23 experimental runs, 5 non-normal runs were included to investigate the pilot's awareness and reaction to unexpected events and conditions (e.g., failures). The non-normal data are critical determinants in the underlying safety of all-weather operations. Due to paper page-limit constraints, these data are not reported herein.

For approach and landing runs, the experiment matrix (Table 1) consisted of a partial-factorial combination of display type (HUD, XVS with HUD FOV, or XVS with Full FOV), AOA (low or high) and peripheral cues in side windows (absent or present). The MALSR ALS (Medium-Intensity Approach Lighting System with Runway Alignment Indicator) was held fixed for the approach and landing runs listed in Table 1.

Table 1. Approach and Departure Run Matrix

	HUD	XVS with HUD FOV	XVS with Full FOV
VMC Low AOA Approach	✓	✓	✓
IMC Low AOA Approach	✓	✓	✓
VMC High AOA Approach		✓	
IMC High AOA Approach		✓	
VMC Departure	✓	✓	✓
IMC Departure	✓	✓	✓

Four additional runs were conducted to test for display type (HUD or XVS with Full FOV) and approach lighting system (VFR, ALSF-2 [Approach Lighting System with Sequenced Flashing Lights]) effects. The low AOA condition and the IMC visibility level were held fixed for these comparisons. These four runs were compared to the 2 analogous MALSR ALS runs (HUD and XVS with Full FOV) from the Table 1 experimental matrix to test for ALS effects. Due to page limitations, the results for the ALS analyses are not reported herein.

For departure runs, the experiment matrix (Table 1) consisted of a full-factorial combination of display type and peripheral cues in the side windows for a total of 6 runs. Only low AOA conditions were flown for the departure runs.

Measures

During each approach and landing run, path error, pilot control inputs, and touchdown performance (fore or aft of touchdown zone, and distance left or right of centerline) were analyzed. During taxi operations, centerline tracking and taxi speed were measured. For departure runs, centerline tracking, heading and climb rate maintenance, and altitude capture were measured.

After each run, pilots completed a run questionnaire consisting of the NASA Task Load Index (TLX) workload rating [12], Situation Awareness Rating Technique (SART)[12], and six Likert-type (5-point) questions specific to different constructs of making a stabilized and safe approach to landing, taxiing (when appropriate), or departure.

After data collection was completed, pilots were administered two paired comparison tests: the Situation Awareness – Subjective Workload Dominance (SA-SWORD) [13] and Subjective Workload Dominance (SWORD) [12] techniques. The pilots also completed a post-test questionnaire to elicit comments on using the different display concepts, with and without peripheral cues, for conducting 1) low and high AOA approaches without a visual segment, 2) surface operations and 3) departures.

Test Conduct

The subjects were given a 1-hour briefing to explain the experiment purpose, HUD and XVS concepts, pilot procedures, and the evaluation tasks. After the briefing, a 1-hour training session in the IFD was conducted to familiarize the subjects with the aircraft handling qualities, display symbologies, pilot procedures, and controls. The pilot's responsibility for maintaining safe operations at all times was stressed. Data collection lasted approximately 4.5 hours and was followed by debriefings which included a final questionnaire. The entire session including lunch and breaks lasted approximately 8 hours.

Results

For the approach path error (deviation) data and landing performance data, repeated-measures analyses of variance (ANOVAs) were conducted for the factors of display type (HUD, XVS with HUD FOV, XVS with Full FOV) and peripheral cues (absent, present) for the fixed low AOA and MALSR ALS condition. Repeated-measures ANOVAs were also conducted on the XVS with Full FOV path deviation data to assess if there were AOA or peripheral cue differences for localizer and glide slope tracking. Additionally, motion (with, without) effects on path deviation data and landing performance data were evaluated by using a 2x3x2 mixed-factorial ANOVA with motion as the between-subjects factor and display type and peripheral cues as the within-subjects factors. The 'without' motion runs were collected in a previously conducted fixed-base IFD simulation experiment [8] that manipulated the same independent variables as the motion-base IFD experiment reported herein.

For the post-test paired comparisons, motion (with, without) effects on SA and workload were evaluated by using a 2x4 mixed-factorial ANOVA with motion as the between-subjects factor and display type as the within-subjects factor.

Approach Performance

Approach performance was assessed using rms (root mean square) localizer deviation (in dots) and rms glide slope deviation (in dots). These parameters correspond intuitively to the establishment and maintenance of a stabilized approach to landing – an important safety measure.

The approach data were analyzed from 1000 ft to 100 ft HAT for the normal runs that ended in a landing. The beginning altitude value was chosen since the pilots were instructed to have the aircraft stabilized on the approach by 1000 ft HAT else, they should perform a go-around.

Both the rms localizer and rms glide slope deviation data had non-normal distributions. Logarithmic-transformed rms localizer and glide slope deviation data provided normal distributions and were used in the repeated-measures ANOVAs for the path deviation data. Mauchly's test showed that the condition of sphericity (equal differences between data taken from the same participant) had been met for each of the ANOVAs conducted on the path deviation data.

When means of the logarithmic path deviation data are transformed back to original units, the mean reported is actually the geometric mean [14] of the path deviation data and that is what is reported herein.

Localizer Angular Deviation

Display Type/Peripheral Cues Effects

The interaction between display type and peripheral cues was statistically significant (F(2, 22)=7.513, p<.01) for rms localizer deviation (Table 2). Pilots flew a more precise lateral path when peripheral cues were absent (IMC condition) compared to when there were present (VMC condition) with the HUD and XVS with Full FOV displays; however, the opposite trend was true for the XVS with HUD FOV display where pilots flew more precise laterally when peripheral cues were present compared to when they were absent.

Table 2. Approach Path Deviation

		HUD		**XVS w/ HUD FOV**		**XVS w/ Full FOV**	
		IMC	**VMC**	**IMC**	**VMC**	**IMC**	**VMC**
Geometric Mean	**rms loc dev (dots)**	0.01	0.02	0.02	0.01	0.02	0.02
	rms gs dev (dots)	0.14	0.15	0.25	0.20	0.17	0.12

AOA/Peripheral Cue Effects

There were no significant (p>0.05) differences between the main factors, AOA and peripheral cues, or their second-order interaction for rms localizer deviation (overall geometric mean=0.018 dots).

Motion Effects

Motion was significant for rms localizer deviation, F(1,33)=9.820, p<0.01. Pilots had significantly better lateral path tracking when they flew with motion (geometric mean=0.017 dots) compared to when they flew without it (geometric mean=0.027). There were no significant (p>0.05) second-order motion effects for this measure.

Glide Slope Angular Deviation

Display Type/Peripheral Cues Effects

Display type (F(2,22)=15.588, p<0.001) was significant for rms glide slope deviation, but peripheral cues and the interaction between display type and peripheral cues was not significant (p>0.05). Pilots had significantly better glide path performance with the HUD and XVS with Full FOV display than with the XVS with HUD FOV display (Table 2).

AOA/Peripheral Cue Effects

Peripheral cues (F(1,11)=5.683, p<0.05) were significant for rms glide slope deviation but AOA and the interaction between peripheral cues and AOA were not significant (p>0.05) for this measure. Pilots had significantly better glide path performance when peripheral cues were present (geometric mean=0.142 dots) compared to when they were absent (geometric mean=0.177 dots).

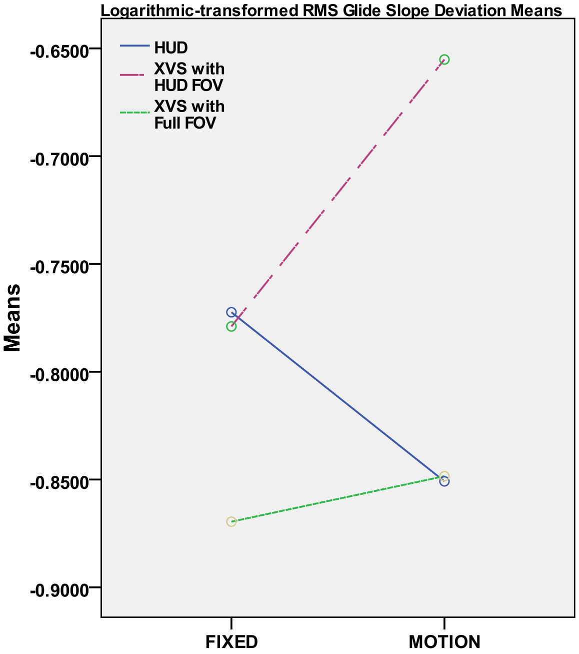


Figure 6. Logarithmic-transformed RMS Glide Slope Deviation Means for Display Type

<u>Motion Effects</u>

The second-order interaction between display and motion was significant (F(2,66)=5.85, $p<0.01$) for rms glide slope deviation (Figure 6). (Note that in Figure 6, the logarithmic-transformed means are shown. When transformed back to original units, a more negative-valued logarithmic mean will indicate a lower-valued geometric mean than a less negative-valued logarithmic mean). Glide path tracking performance of the 3 display types differed in motion and fixed-base operations. Comparing motion to fixed-base runs, the HUD had improvements in glide path tracking and the two XVS displays had degradations in this measure. However, if you look at the motion run (logarithmic-transformed) means of rms glide slope deviation in Figure 6, nearly equivalent values are shown between the HUD and XVS with Full FOV displays. The main factor motion and the second-order interaction between peripheral cues and motion were not significant ($p>0.05$) for rms glide slope deviation.

Objective Approach Standards Analysis

The Joint Aviation Authorities (JAA) Joint Aviation Requirement (JAR) All Weather Operations (AWO) performance-based approach standard for go-around rate (AWO-202) in low-visibility approaches with decision heights below 200 ft and down to 100 ft was also applied in the objective data analysis [15]. Specifically, the standards specify that no more than 5% of the approaches will have localizer deviations greater than 1/3 dot or glideslope deviations greater than 1 dot between 300 ft and 100 ft HAT for certification acceptance. These low-visibility approach standards were not written specifically as quantitative performance standards for advanced vision systems (such as XVS) operations, but are applied herein for comparative purposes.

The Continuous Method [15] technique was employed to calculate the probability of success, P(α), of meeting the AWO exceedance criteria (1/3 dot localizer, 1 dot glideslope) with required levels of confidence with the different display concepts flown. The probabilities of success for meeting the AWO localizer and glideslope criteria are shown, broken down by AOA, display type and visibility condition, in Table 3 for this motion-base experiment. Also included in Table 3 are the applicable probabilities of success for a fixed-base IFD XVS experiment [8] that manipulated these same independent variables.

The data in Table 3 shows that localizer tracking was maintained, irrespective of the display being flown, approach angle-of-attack, the absence or presence of peripheral cues in the side windows, or the absence or presence of simulator motion. For both the fixed-base and motion-base runs, the only display concept successfully meeting the JAR AWO-202 localizer and glide slope criterion (greater than 95% of the time) was the low AOA XVS with Full FOV display concept flown with peripheral cues in the side windows (in bold, Table 3). This color, uncollimated, display concept showed conformal imagery over a 34° vertical FOV.

There appears to be a motion/collimation effect in glide slope tracking performance. The collimated HUD concepts had improvements in glideslope tracking performance when the simulator was in motion compared to when it was in fixed-base; while, the uncollimated XVS with HUD FOV concepts had degradations in this measure when the simulator was in motion compared to when it was in fixed-base. There also appears to be a peripheral cue/uncollimated display effect for glide slope tracking. For the uncollimated XVS concepts, there were glide slope tracking improvements when peripheral cues were present compared to when there were none. There does not appear to be a motion effect on whether a pilot completed a landing or not as there were no go-arounds for the motion-base runs and only 1 go-around for the fixed-base runs.

Table 3. Probabilities of Success in Meeting the AWO Localizer and Glideslope Criteria without a Visual Landing Segment in Fixed-Base and Motion-Base Simulation Runs

Display	AOA	Wx	Localizer P(α)		Glideslope P(α)		# Go-Around/#Total Runs	
			Fixed-base	Motion-base	Fixed-base	Motion-base	Fixed-base	Motion-base
HUD	Low	IMC	100	100	67	88	0/24	0/12
HUD	Low	VMC	100	100	78	83	0/24	0/12
XVS HUD FOV	Low	IMC	100	100	81	55	1/24	0/12
XVS HUD FOV	Low	VMC	100	100	94	72	0/24	0/12
XVS Full FOV	Low	IMC	100	100	93	75	0/24	0/12
XVS Full FOV	**Low**	**VMC**	**100**	**100**	**96**	**96**	**0/24**	**0/12**
XVS Full FOV	High	IMC	100	100	84	74	0/24	0/12
XVS Full FOV	High	VMC	100	100	88	81	0/24	0/12

Note: Approaches using MALSR ALS.

Landing Performance

Landing performance was assessed using touchdown longitudinal position (in ft), lateral position (in ft) and sink rate (in ft/sec, or fps). All three touchdown measures had normal distributions. Mauchly's test showed that the condition of sphericity had been met for each of the ANOVAs conducted on the landing data except for the motion effects second-order interaction of display and peripheral cues for touchdown lateral position, $\chi^2(2)=8.592$. Therefore, degrees of freedom were corrected using Greenhouse-Geisser estimates of sphericity (ε=.81).

Display Type/Peripheral Cues Effects

Display type (F(2,22)=7.065, p<0.01) was significant for touchdown longitudinal position. The pilots landed significantly further beyond the threshold when flying with the HUD (mean=1823 ft) than when flying with the XVS with HUD FOV (mean=1496 ft). Neither the HUD nor XVS with HUD FOV were significantly different than the XVS with Full FOV (mean=1660 ft) for this measure.

The interaction between display type and peripheral cues (F(2,22)=13.831, p<0.01) was significant for touchdown lateral position (Figure 7). Operationally though these differences were not significant as the largest lateral deviation from centerline was 6 ft.

All other main effects and second order interactions were not significant (p>0.05) for the touchdown performance measures.

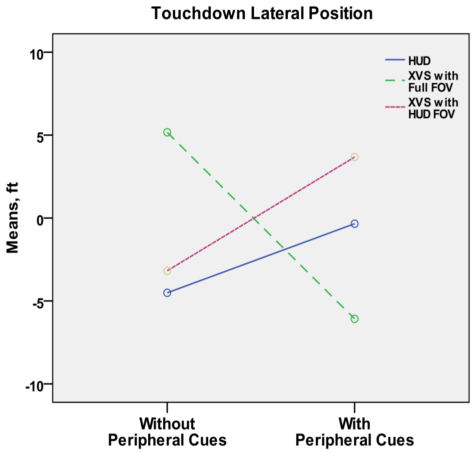


Figure 7. Lateral Touchdown Position – Display by Peripheral Cues

Motion Effects

Motion was significant for touchdown sink rate F(1,32)=34.521, p<0.01. Pilots had significantly less sink rate when they flew with motion (mean=-3.1 fps) compared to when they flew without it (mean=-5.7

fps). There were no significant ($p>0.05$) second-order motion effects for this measure.

No motion effects were found for the touchdown longitudinal or lateral position measures.

Objective Landing Standards Analysis

Existing JAR AWO [15] performance-based landing standards (AWO 131) for longitudinal position and lateral position from centerline were applied in the objective landing data analysis. Specifically, the standards state that no longitudinal touchdown earlier than a point on the runway 200 ft from the threshold or beyond 2700 ft from the threshold and no lateral touchdown with the outboard landing gear more than 70 ft from the runway centerline to a probability of 1×10^{-6}. These standards pertain to the general concept of low-visibility approach and landings, but were not written specifically for operations with advanced vision systems such as XVS.

This experiment used an aim point located 1000 ft from the runway threshold. For the simulated 757 aircraft, the outboard landing gear would be 70 ft from the centerline when the fuselage (the recorded lateral landing position reported herein) is at 58 ft lateral deviation from centerline, assuming no crab angle at touchdown. In Figure 8, the touchdown data are shown, broken out by display concept and AOA condition but collapsed across peripheral cue influence. Included on this plot (in red, dashed rectangle) is the +/-58 ft lateral and 200 ft to 2700 ft longitudinal touchdown footprint defined in the JAR AWO landing criteria.

Visual inspection of the data in Figure 8 show that all display concepts tested in motion, regardless of the AOA or peripheral cue condition, were within the JAR lateral and longitudinal touchdown criteria footprint. In contrast, the fixed-base study looking at the same display type/angle of attack concepts did not all meet the JAR touchdown criteria [8]. Specifically in that study, 4 HUD low AOA fixed-base runs landed beyond 2700 feet from the threshold.

These data were analyzed against the $1x10^{-6}$ probability requirements. The analyses show that the lateral landing position met the 10^{-6} probability criteria (*i.e.,* within 58 ft of centerline) for all the display type/angle of attack concepts presented in Figure 8.

Satisfying the JAR AWO (low-visibility landing) longitudinal touchdown criteria to a $1x10^{-6}$ probability was not met with any of the display concepts tested.

Approach and Landing Performance Discussion

Elimination of the visual segment of the approach had no adverse affects on localizer tracking as it was excellent from 1000 ft to 100 ft HAT and well within JAR AWO approach criteria for decision heights below 200 ft and down to 100 ft regardless of display size (large FOV or HUD FOV), AOA (low or high), collimation (with or without) or whether the pilot had peripheral cues or not. However, glide slope tracking from the required stabilized approach altitude of 1000 ft to 100 ft HAT appears to be affected by display size (*i.e.*, FOV) and collimation. The monochrome, collimated HUD and color, uncollimated XVS with Full FOV display had (statistically equivalent) glide path performance improvements over the XVS with HUD FOV display. This finding may indicate that collimation is not a requirement for an XVS display to have adequate approach path maintenance if the XVS display is large enough and employs color. In fact, JAR AWO glideslope tracking criteria was only met by the low AOA condition in the XVS with Full FOV display concept with peripheral cues in the side windows.

Motion appears to improve glide path tracking for the collimated displays, lateral path tracking and touchdown sink rate for all the displays tested, and not degrade landing performance. All touchdowns occurred within the AWO touchdown box irrespective of display type or AOA when the simulator was in motion.

The lateral touchdown data shows that the JAR AWO criteria were met with $1x10^{-6}$ probability for all motion concepts using the MALSR ALS. Lateral and longitudinal positioning for touchdown was not a problem across any of the experimental display concepts.

A widely perceived assumption is that peripheral cues are necessary for good flare and touchdown performance. This assumption was not supported by these data. No effect from the absence and presence of peripheral cues was found. This result supports other data [16] that peripheral cues are not as important on landing performance as generally assumed but a significant FOV in the forward field of view - as indicated by the large FOV XVS performance - is more influential. Further, these data highlight the importance of having motion cueing effects for representative sink rate at touchdown performance, comparable to real-world performance expectations [16].

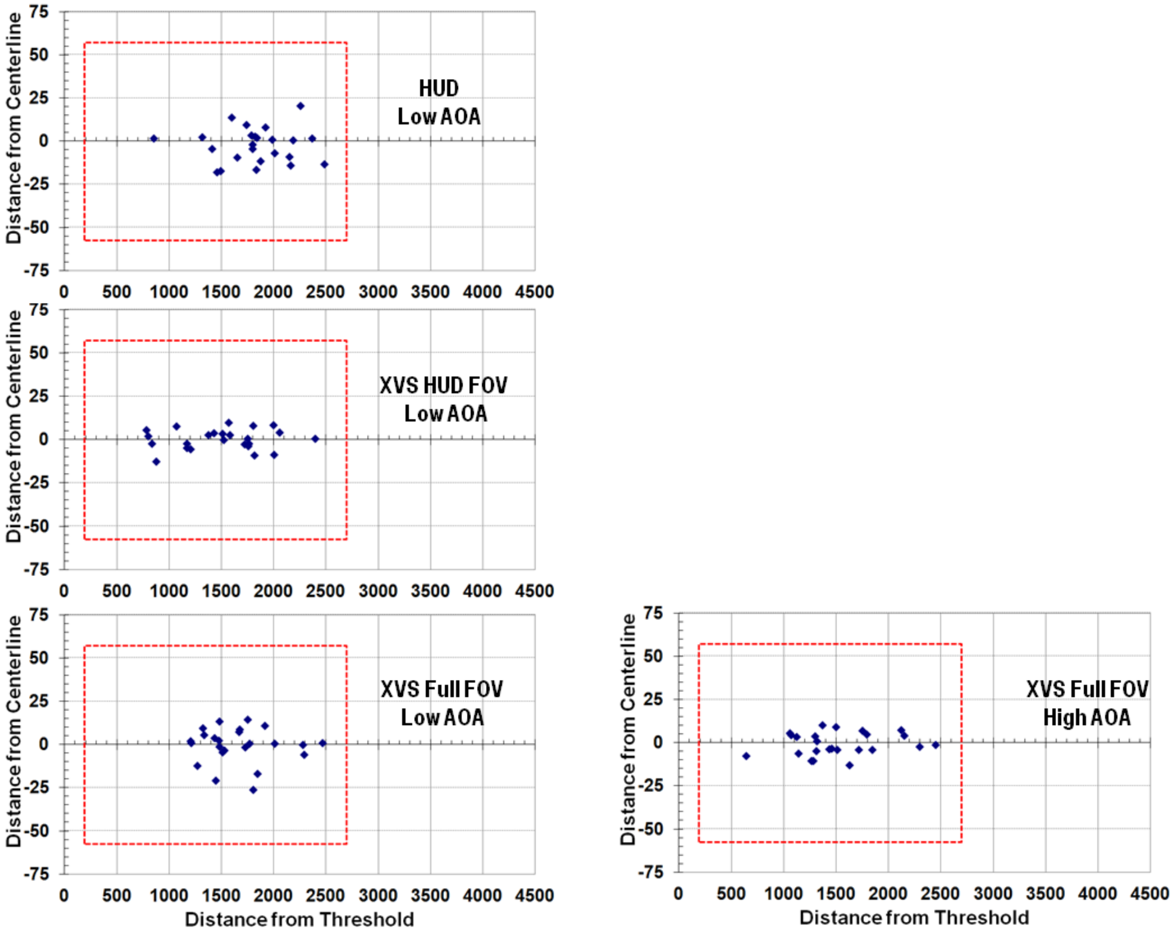


Figure 8. Touchdown Data for Display Concepts for fixed MASLR ALS

Mental Workload-SWORD

Post-test, pilots were administered the paired-comparison SWORD scale that enabled comparative ratings of mental workload. Mental workload was defined for the pilots as “the amount of cognitive resources available to perform a task and the difficulty of that task.” The pair-comparison test was structured to compare the effects of color/collimation and peripheral cues (*i.e.,* uncollimated, color XVS with HUD FOV flown in VMC; uncollimated, color XVS with HUD FOV flown in IMC; collimated, monochrome HUD flown in VMC; collimated, monochrome HUD flown in IMC) flown by the EP. Note that this comparison only considered the display types with the 26 deg x 21 deg FOV.

Mauchly’s test indicated that the assumption of sphericity had been violated for the main factor display type, $\chi^2(5)=35.377$. Therefore, degrees of freedom were corrected using Greenhouse-Geisser estimates of sphericity ($\varepsilon=.67$). The post-test paired-comparison SWORD data indicated that display type (F(2.00,67.98)=29.610, p<0.01) was highly significant for the pilot ratings of mental workload. Contrasts showed three overlapping subsets for the mental workload ratings 1) uncollimated XVS with peripheral cues, uncollimated XVS without peripheral cues (lowest workload), 2) uncollimated XVS without peripheral cues and collimated HUD with peripheral cues, and 3) collimated HUD without peripheral cues (highest workload). The main factor motion and the second-order interaction between motion and display were not significant (p>0.05) for mental workload.

Situation Awareness – SA-SWORD

Post-test, pilots were administered the paired-comparison SA-SWORD scale that enabled comparative ratings of situation awareness. For these comparisons, SA was defined as "the pilot's awareness and understanding of all factors that will contribute to the safe flying of their aircraft under normal and non-normal conditions." The pair-comparison test was structured to compare the effects of collimation and peripheral cues (*i.e.,* uncollimated, color XVS with HUD FOV flown in VMC; uncollimated, color XVS with HUD FOV flown in IMC; collimated, monochrome HUD flown in VMC; collimated, monochrome HUD flown in IMC) flown by the EP. Note that this comparison only considered the display types with the 26 deg x 21 deg FOV.

Mauchly's test indicated that the assumption of sphericity had been violated for the main factor display type, $\chi^2(5)=37.370$. Therefore, degrees of freedom were corrected using Greenhouse-Geisser estimates of sphericity ($\varepsilon=.73$). The post-test paired-comparison SA-SWORD data indicated that display type ($F(2.19,74.51)=67.587$, $p<0.01$) was highly significant for the pilot ratings of situation awareness. Contrasts showed four unique subsets for the SA ratings 1) uncollimated XVS with peripheral cues (highest SA), 2) uncollimated XVS without peripheral cues, 3) collimated HUD with peripheral cues, and 4) collimated HUD without peripheral cues (lowest SA). The main factor motion and the second-order interaction between motion and display were not significant ($p>0.05$) for situation awareness.

Mental Workload and Situation Awareness Discussion

The subjective post-test ratings revealed that display color was a stronger influence on mental workload and SA than collimation. The workload and SA ratings also indicated that within the same display type (HUD or XVS) the presence of peripheral cues provided mental workload and SA improvements. These results were also supported by pilot comments during the post-test interviews.

Concluding Remarks

An experiment was conducted to investigate the use of XVS technologies as enabling technologies for future all-weather operations. The experimental objectives were to evaluate some of the design requirements of an XVS - without the need for forward-facing windows - and to determine the interaction of XVS and peripheral vision cues for terminal area and surface operations. . Objective results indicate that elimination of the visual segment of the approach had no adverse affects on localizer tracking as it was excellent regardless of the display type (XVS, HUD) and angle-of-attack (low, high) condition being evaluated or whether or not there were peripheral cues in the side windows. Motion cueing appears to have improved localizer tracking and touchdown sink rate across all displays.

The data showed some evidence of a display collimation effect (*i.e.,* when comparing XVS vs. HUD) for glideslope tracking performance. However, the magnitude of this effect did not impact landing performance. There also appears to be a peripheral cue/uncollimated display effect for glide slope tracking as improvements were found when peripheral cues were present while using the XVS display (HUD-like FOV and Full FOV).

Touchdown performance was satisfactory with the HUD and XVS displays tested. All approaches resulted in landings that were within the current standard for landing touchdowns, but not unexpectedly, the longitudinal touchdown dispersions were too large to meet a 10^{-6} probability condition.

The subjective data suggests that color, not collimation, was the primary effect for workload and situation awareness improvements found with the XVS display compared to the HUD display.

In this experiment, it was impractical to completely divorce the collimation and display color variables, so the effects are confounded. However, if the collimation/color results found in this test could be validated, a less-complex non-collimated display could be suitable for an XVS-type system. Future research should include the validation of these results by flight testing in an operationally-realistic environment where vestibular and peripheral vision effects are accurately represented.

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