NASA/TP-2003-212177

Flight Test Comparison of Synthetic Vision Display Concepts at Dallas/Fort Worth International Airport

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May 2003

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May 2003

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Nomenclature

ADI	attitude direction indicator
AGL	above ground level, ft
ALT	altimeter
ANOVA	analysis of variance
AR	display aspect ratio
ARIES	Airborne Research Integrated Experimental System
A/S	airspeed indicator
AS/ALT	airspeed altitude
ATC	air traffic control
Ave	average
CDI	course deviation indicator
CFIT	controlled flight into terrain
CPU	central processing unit
collrms	RMS of pilot's longitudinal control input, deg
DEM	digital elevation model
DFW	Dallas/Fort Worth International Airport
DGPS	differentially corrected Global Positioning System
DME	distance measuring equipment
EADI	electronic attitude direction indicator
EFIS	electronic flight instrumentation system
EGPWS	enhanced ground proximity warning system
EP	evaluation pilot
ERP	eye reference point
EVS	enhanced vision system
F	population distribution for continuous variables

FAA	Federal Aviation Administration
FDRS	flight deck research station
FLIR	forward-looking infrared
FOV	field of view
GA	generic A-size display
GD	generic D-size display
Generic-A	generically textured size-A display
Generic-D	generically textured size-D display
Generic-X	generically textured size-X display
Generic-HUD	generically textured head-up display
GPS	Global Positioning System
GS	glide slope
GX	generic X-size display
gsrms	RMS value of glide-slope deviation, dots
H	horizontal FOV, deg
HDD	head-down display
HSI	horizontal situation indicator
HUD	head-up display
IF	infrared
ILS	instrument landing system
IMC	instrument meteorological conditions
IVSI	instantaneous vertical situation indicator
LaRC	Langley Research Center
LCD	liquid crystal display
LOC/GS	localizer glide slope
locrms	RMS of localizer error, dots

Max	maximum value
Mbytes	10^6 bytes
MF	minification factor
MFD	multi-function display
Min	minimum value
MSL	mean sea level, ft
maxcut	maximum difference between true track of aircraft and target runway heading, deg
maxfov	maximum field of view selected, deg
maxroll	maximum value for aircraft roll angle, deg
meanfov	mean field of view selected, deg
minfov	minimum field of view selected, deg
minroll	minimum value for aircraft roll angle, deg
NASA	National Aeronautics and Space Administration
ND	navigation display
n	number of samples
nits	unit of brightness
PAPI	precision approach path indicator
PC	personal computer
PFD	primary flight display
Photo-A	photo realistically textured size-A display
Photo-D	photo realistically textured size-D display
Photo-X	photo realistically textured size-X display
Photo-HUD	photo realistically textured HUD
PR	photo-realistic
p	statistical level of significance
ppi	pixels per inch

RMS	root mean square
RWY	runway
resagl	above ground altitude of aircraft when tracking phase criteria initially satisfied, ft
resorxcg	distance from initial runway threshold of aircraft when tracking phase criteria initially satisfied, ft
rollrms	RMS of pilot's aircraft roll angle, deg
rudrms	RMS of pilot's directional control input, deg
SA	situation awareness
SCRAMnet	Shared Common Random Access Memory network
SP	safety pilot
Stdev	standard deviation
S-VHS	super video home system (video format 400 lines at 32 Hz)
SVS	synthetic vision systems
SVS-GE	synthetic vision systems graphics engine
SVS-RD	synthetic vision systems research display
SXVGA	super XVGA (1280 × 1024 resolution)
TCAS	Traffic Alert and Collision Avoidance System
TTA	technology transfer area
V	vertical FOV, deg
VASI	visual approach slope indicator
VFR	visual flight rules
VMC	visual meteorological conditions
VVI	vertical velocity indicator
whlrms	RMS of pilot's lateral control input, deg
XVGA	extended video graphics array (1024 × 786 resolution)

Summary

A goal of the synthetic vision systems (SVS) project of the National Aeronautics and Space Administration's (NASA) Aviation Safety Program is to eliminate poor visibility as a causal factor in aircraft accidents as well as enhance operational capabilities of all aircraft through application of SVS technology. Limited visibility is the single most critical factor affecting both the safety and capacity of worldwide aviation operations. In commercial aviation, over 30 percent of all fatal accidents worldwide are categorized as controlled flight into terrain (CFIT) accidents in which a fully functioning airplane is inadvertently flown into the ground, water, or an obstacle. SVS technology will allow this *visibility* problem to be solved with a *visibility* solution, as better pilot situation awareness during low-visibility conditions can be provided by synthetic vision displays. These displays employ computer-generated terrain imagery to present three-dimensional perspective, out-the-window scenes with sufficient information and realism to enable operations equivalent to those of a bright, clear day, regardless of the outside weather conditions, for increased situation awareness.

To introduce SVS display technology into as many existing aircraft as possible, a retrofit approach was defined. This approach employs existing head-down display (HDD) capabilities, such as electronic attitude director indicators (EADIs) or primary flight displays (PFDs) for glass cockpits (cockpits already equipped with raster-capable HDDs) and head-up display (HUD) capabilities for the other aircraft. This retrofit approach was evaluated and initially validated for typical nighttime airline operations at a major international airport. Overall, 6 evaluation pilots performed 75 research approaches, accumulating 18 hours of flight time evaluating SVS display concepts using the NASA Langley Research Center's Airborne Research Integrated Experimental System (ARIES) Boeing B-757-200 aircraft at the Dallas/Fort Worth (DFW) International Airport.

The SVS HDD concepts evaluated included variations in display size, with pilot-selectable field of view (FOV) and methods of terrain texturing. As employed in this report, FOV refers to the horizontal FOV of the SVS image being displayed to the pilot. Vertical FOV was adjusted to maintain the aspect ratio of the various display concepts tested. Subsequent discussion regarding FOV and its inherent value to SVS displays is provided later in this report. SVS HUD concept evaluations also included variations in the method of terrain texturing.

All pilots acknowledged the enhanced situation awareness provided by all the SVS (HDD and HUD) concepts. Specific results indicated that effective applications of SVS display technology can be accomplished in aircraft equipped with HDDs as small as size-A (5.25 in. wide by 5 in. tall) using pilot-selectable FOV. Regardless of display size, pilots consistently reduced the selected FOV to approximately 30° or less for close-in final approach segments. Therefore, the selected FOV/phase-of-flight result previously mentioned can also be expressed as follows: as range to touchdown decreased, the SVS imagery moved towards a conformal representation of the terrain outside the aircraft (i.e., objects subtended the same viewing angles on the SVS display as in the real world). This result was also true for larger display sizes in which specific FOVs created more nearly conformal SVS imagery than the smaller display sizes.

Two terrain-texturing techniques were employed for this flight test. One method of terrain texturing, referred to as generic texturing, involved the selection of terrain color based on absolute altitude. The other method of terrain texturing, referred to as photo-realistic texturing, employed ortho-rectified aerial photographs. All but one of the pilots preferred the photo-realistic terrain-texturing technique over the generic texturing technique for both HDD and HUD applications.

For aircraft without raster-capable HDDs, the feasibility of the concept of retrofitting SVS display technology with HUDs was verified for nighttime operations. Pilots also commented that presentation of SVS imagery on the HUD, with conformal imagery, was preferred over the HDDs. In addition, the pilot's ability, during a runway change maneuver, to track the extended runway centerline and reduce localizer tracking error was significantly better for the SVS HUD concepts than for the SVS HDD concepts.

The results from this flight test establish the SVS retrofit concept, regardless of display size, as viable for the conditions tested. Future assessments need to extend the evaluation of the SVS retrofit approach to operations in an appropriate, terrain-challenged environment and with testing in daytime conditions.

Introduction

A goal of the synthetic vision systems (SVS) project of the NASA Aviation Safety Program is to eliminate poor visibility as a causal factor in aircraft accidents as well as to enhance operational capabilities of SVS-equipped aircraft through application of SVS technology. Limited visibility is the single most critical factor affecting both the safety and capacity of worldwide aviation operations. In commercial aviation, over 30 percent of all fatal accidents and the greatest cause of fatalities worldwide are categorized as controlled flight into terrain (CFIT) accidents in which a fully functioning airplane is inadvertently flown into the ground, water, or an obstacle (ref. 1). SVS technology will allow this *visibility* problem to be solved with a *visibility* solution, as better pilot situation awareness during low-visibility conditions can be provided by synthetic vision displays. These displays employ computer-generated terrain imagery to present three-dimensional, perspective out-the-window scenes with sufficient information and realism to enable operations equivalent to those of a bright, clear day, regardless of the outside weather conditions, for increased situation awareness.

To introduce SVS display technology into as many existing aircraft as possible, a retrofit approach was defined. This approach employs existing head-down display (HDD) capabilities for glass cockpits (cockpits already equipped with raster-capable HDDs) and head-up display (HUD) capabilities for the other aircraft.

The SVS retrofit approach was the focus of the Dallas/Fort Worth (DFW) International Airport flight test effort, which was conducted to address several critical aspects of SVS display implementation into the commercial transport fleet. The SVS display design aspects addressed by this flight test were (1) the establishment of field of view (FOV) recommendations for appropriate HDD sizes based on phase of flight, (2) the determinations of the effect of HDD size on pilot performance and situation awareness (SA), (3) the determination of the effect of SVS HUD concepts on pilot performance and SA, (4) the determination of the effect of terrain texturing for both HUD and HDD SVS display concepts, (5) the comparison of pilot performance and qualitative comments between SVS HDD and HUD concepts, and (6) the evaluation and demonstration of SVS display concepts at a large international airport under nighttime conditions.

FOV is a new design parameter for SVS variants of primary flight displays (PFDs) and electronic attitude direction indicators (EADIs). As employed in this report, unless otherwise noted, FOV refers to the horizontal FOV of the SVS image being displayed to the pilot. Current PFDs and EADIs convey attitude information to the pilot through the use of symbology developed and refined over several decades. Specifically, pitch information is provided through some type of pitch scale with a reference waterline symbol, and bank information is provided via a roll scale. In general, pitch scales display approximately 60° of pitch attitude, and roll scales are tailored to meet the specific needs of the aircraft for which they are designed.

In addition to attitude information, SVS displays incorporate computer-generated terrain to increase the pilots' SA. In the process of creating SVS displays, the computer-generated terrain is integrated with the symbology. One part of the integration is matching the vertical FOV of the SVS imagery with the pitch scale. The presence of SVS imagery on PFDs or EADIs dramatically alters the character of the information being provided to the pilot and presents another design consideration to address. Variations in FOV have been studied (ref. 2), with results suggesting that different phases of flight may affect optimum FOVs.

Three different various size HDD configurations were evaluated during this flight test to explore retrofit concepts of SVS display technology into existing glass cockpits. One display configuration, referred to as size-A, was typical of the B-757-200 EADI and horizontal situation indicator (HSI) with separate airspeed, altitude, and vertical speed gauges. Another display configuration, referred to as size-D, was typical of a Boeing B-777, with side-by-side presentation of an integrated PFD and navigation display (ND). The third HDD configuration, referred to as size-X, featured an enlarged PFD to replicate future HDD concepts and a smaller ND. Evaluation pilots (EPs) could control the FOV of the HDD EADI or PFD as they maneuvered the aircraft.

The NASA SVS project is also investigating the potential of using existing HUD technology as a retrofit solution in non-glass cockpits. As such, the HUD is used in an unconventional manner. The terrain database scene is presented on the HUD as a raster image with stroke symbology overlaid upon it and is called the opaque terrain/clear sky HUD concept. It is similar to enhanced vision system (EVS) concepts, which typically use advanced imaging sensors to penetrate weather phenomena such as darkness, fog, haze, rain, and/or snow, and the resulting enhanced scene is presented on a HUD, through which the outside real world may be visible. These EVS concepts have been the subject of experiments for over two decades, and the military has successfully deployed various implementations.

In the opaque HUD concept, the terrain database scene replaces the sensor image. Unlike EVS displays, the opaque SVS HUD concept uses a clear sky rather than a sensor image of the sky, so there is no obstruction of that area of the display. Below the horizon, the raster image can obstruct the view of the outside real world and become completely opaque for a range of raster brightness (hence the use of the word opaque). Obstruction of the outside real world scene by such a display is a recognized certification issue. In addition to the raster image, nominal flight information symbology found on most airline HUDs was overlaid on the HUD imagery.

For both the HDD and HUD SVS concepts, an evaluation of two terrain-texturing methods was conducted. One terrain-texturing option, referred to as generic texturing or the generically textured terrain, based the terrain color on the absolute terrain height, with higher elevations receiving a lighter color. The other terrain-texturing option, referred to as photo-realistic texturing, or the photo realistically textured terrain, used ortho-rectified photographic images to texture the terrain, generating a highly realistic environment. Generically textured terrain is attractive because it reduces the demand for computational resources to generate the resulting computer-generated image. Photo realistically textured terrain, however, requires much more powerful computers to achieve acceptable display update rates. The current research attempts to quantify the relative value of photo-realistic versus generic terrain-texturing methods.

There were major differences between the HUD and HDD concepts evaluated. These differences included, for the HUD, fixed image conformality, the larger FOV of the conformal image, collimation, and location, compared to the HDDs. The comparison of HUD and HDD SVS applications was therefore of major interest and involved analyses of pilot performance and pilot comments received during the flight test. Pilots provided comments regarding the relative capabilities of HUD versus HDD concepts. In addition, comparison of pilot performance data for HUD to HDD concepts revealed statistically significant difference results that agree with previous research. Only minor differences in symbology were included in this test. Symbology differences were limited to the method of presentation of altitude and airspeed. For the HUD concept, airspeed and altitude were presented digitally, whereas for the HDD concepts, airspeed and altitude were presented in analog round-dial (size-A) or tape (size-D and size-X) format.

Background

The ability of a pilot to ascertain critical information through visual perception of the outside environment can be limited by various weather phenomena such as rain, fog, and snow, and by darkness typical of night operations. Since the beginning of flight, the aviation industry has continuously developed various devices to overcome low-visibility issues, such as attitude indicators, radio navigation, instrument landing systems, and many more. Recent advances include moving map displays, improvements in navigational accuracy from the Global Positioning System (GPS), and enhanced ground proximity warning systems (EGPWSs). All aircraft information displays developed to date require the pilot to perform various additional levels of mental model development and maintenance and to do information decoding in a real-time environment when outside visibility is restricted.

Better pilot situation and spatial awareness during low-visibility conditions can be provided by SVS perspective flight-path displays. Synthetic vision technology may allow the issues associated with limited visibility to be solved with a visibility-based solution, giving every flight the safety of a clear, daylight operation, alleviating much of the mental workload required of today's pilots. Situation awareness (SA) can be defined as the pilot's integrated understanding of the factors that contribute to the safe operation of the aircraft under all conditions. Spatial awareness (an individual component of SA) can be defined as the pilot's knowledge of ownship position relative to its desired flight route, the runway, terrain, and other traffic. Recent technological developments in navigation performance, low-cost attitude and heading reference systems, computational capabilities, and displays raise the prospect of having SVS displays, in various capacities, in most aircraft. SVS display concepts employ computer-generated terrain imagery to create a three-dimensional perspective presentation of the outside world, with the necessary and sufficient information and realism to enable operations equivalent to those of a bright, clear day, regardless of weather conditions.

References 2 and 3 present discussions and findings regarding background and development of SVS displays. Reference 3 states that it is highly unlikely that with anticipated developments, safety can be increased by extrapolating current display concepts. New functionality and new technology cannot simply be layered onto previous design concepts because the current system complexities are already too high. Better human-machine interfaces require a fundamentally new approach. The fundamental advantage of a perspective flight-path display instead of a conventional display with flight directors is that it continuously provides the pilot with information about the spatial constraints rather than commands to minimize an error independent of the actual constraints. In addition, reference 3 states that elements of the display that provide guidance should not force the pilot to apply a continuous compensatory control strategy. Rather than commanding the pilot what to do, or at best showing only the error with respect to the desired trajectory, guidance and navigation displays should provide information about the margins within which the pilot is allowed to operate. Only in this way can human flexibility be exploited and is a fundamental difference between current displays and SVS displays.

Reference 4 presents the concept of natural versus coded information. Natural information implies that the pilot's method of information acquisition is similar to that experienced in visual meteorological conditions (VMC) by looking out the window. Visual altitude judgment is an example of natural information acquisition. Coded information implies some type of information presentation to the pilot that requires interpretation to comprehend the actual value. An example of coded information is digital radio altitude. Reference 4 asserts that it is better to give the pilot information needed to maintain SA in low-visibility conditions using natural information presentation. By providing a natural presentation of the outside world, SVS displays provide information that is intuitive and easy to process. Assessment of the pilot's ability to interpret and assimilate SVS information was part of this flight test. This flight test effort was conducted to establish recommendations for various SVS human-machine interface issues, such as FOV, display size or type of display (i.e., HDD or HUD), and method of terrain portrayal.

In addition to HDD applications of SVS technology, the current retrofit concept employs HUD technology to facilitate SVS implementation in certain aircraft. Prior HUD research has established various qualities inherent to that type of display device. Reference 5 presents piloted simulation results that compare a HUD to two different HDDs, illustrating the specific points that define the salient differences between these two types of display devices. The display types evaluated were a HUD, a conventional HDD, and a repeat display of the HUD symbology on a small display located cross-cockpit 40 in. from the pilot. Data from reference 5 noted a significant effect on the pilot's ability to track localizer and glide slope and manually maintain airspeed dependent on display type in little or no forward visibility conditions. The HUD demonstrated superior performance, with the HUD repeater display ranked second. The information from reference 5 indicates that display FOV, magnification, symbology, and location were the most likely contributors to the observed differences. The subject flight test effort was conducted, in part, to establish that the application of SVS technology did not alter previous conceptions regarding the relationship of HDD and HUD technologies.

Reference 6 presents piloted simulation results that concern the effects of various display factors for an imaging sensor study (an enhanced vision application) during final approach and touchdown. Of immediate interest to the current investigation are the results for FOV variations with fixed unity magnification and the direct comparisons across magnification factors. For unity magnification, the flare and touchdown performance measures improved with increases in FOV. However, subjective comments indicated a pilot's desire for selectable FOVs, with larger FOVs at greater ranges from the threshold and smaller FOVs for flare and touchdown (all with unity magnification). Comparisons of different magnification factors with a fixed display size (and necessarily different FOVs) showed improved flare and touchdown performance measures with increasing magnification factors (from 0.75 to 1.5). Reference 7 also examined magnification factor effects for contact analog displays. Contact analog displays employ space-stabilized symbology, like runway outlines, to portray salient features of the real world. Pilot performance during approach maneuvers was compared to real world performance, and this study also found improvements with increasing magnification factors. Magnification factors greater than one were required to approach real world performance. One of the primary objectives of the subject flight test experiment was to define strategies for FOV use as applied to SVS displays of various sizes.

Reference 8 presents piloted simulation results for variations of FOV with fixed unity magnification for displays that include tunnel-in-the-sky guidance for curved landing approaches. Few differences were detected in lateral and vertical path tracking errors between 40° and 70° FOV pictorial displays. One facet of the subject flight test study involved the evaluation of a minimal tunnel-in-the-sky concept for SVS displays.

References 9 and 10 indicate some differences in the subject pilot's ability to perform accurate depth and speed judgments for collimated and noncollimated displays. While no specific pilot performance data were obtained from these references, the effects of collimation for SVS displays should be investigated. A limited exploration of the effect of collimation on SVS displays is introduced in this flight test effort through the comparison of results for HUD and HDD concepts.

Numerous publications (refs. 11 through 14) are available that describe various terrain depiction techniques for tactical PFD, HUD, strategic ND, and multi-function displays (MFDs). These techniques include, but are not limited to, ridge lines, grid patterns (equal and nonequal spacing), color-coded contour lines, varying color textures based on elevation, photo-realistic textures, and textures with an embedded grid pattern. In addition to terrain texturing, standard-sized objects (e.g., 100-ft trees) can be placed in the database to give pilots improved height-above-terrain cues. Flight tests in southeastern Alaska of Stanford's tunnel-in-the-sky display (ref. 11) showed that adding a textured terrain skin to the EADI gave pilots a better awareness of their height above the ground. Textures increase terrain realism by increasing the level of detail per polygon, thus providing additional cues for position (height and range) estimates. However, reference 12 warns that photo-realistic textures may inadvertently cause a pilot to give a terrain database more integrity than it actually has due to the "realness" of these textures. Independent means for monitoring the integrity of the terrain elevation model are currently being investigated by researchers within NASA's SVS project. Using the plane's existing weather radar or its radar altimeters are some of the technologies being tested to perform this integrity function. Appropriate methods of terrain portrayal were explored as part of this flight test effort. Two different types of terrain texturing were evaluated in an attempt to develop recommendations for terrain portrayal for SVS displays.

Thus, while data exist addressing some of the display parameters of interest to the SVS investigation, the questions of how big an SVS display should be (size), or what FOV should be shown, remain largely unanswered. Likewise, while there have been many investigations of HUD formats, terrain database HUD investigations have been confined to wireframe/ridge-line presentations rather than opaque raster images. The SVS retrofit concept, and its realization through maturing SVS-related technologies, was the overall objective of this flight test effort. This investigation attempts to enhance the understanding of SVS displays and quantify their actual benefit, in real operations, to establish a viable implementation strategy for all transport aircraft.

Test Equipment

The NASA Langley Research Center (LaRC) Airborne Research Integrated Experimental System (ARIES) aircraft (fig. 1) was used to conduct this flight test. ARIES provided the ability to perform many research projects simultaneously and was an appropriate platform for this flight test. SVS display concepts were presented to the pilot by using either an experimental HUD system or the synthetic vision systems research display (SVS-RD) mounted in the ARIES cockpit. The SVS-RD was a custom packaged flat panel liquid crystal display (LCD) temporarily installed over the display panel of ARIES and had touch-screen input capability. Evaluation pilots were presented various SVS HDD concepts on the SVS-RD display that was mounted over the conventional B-757-200 displays. The HUD system, originally built by Dassault for installation in a SAAB 2000 aircraft, provided stroke conversion of raster-only flight symbology overlaid on raster terrain for display to the evaluation pilot (EP). The SVS graphics engine (SVS-GE) for both displays was a rack mounted Intergraph Z × 1 personal computer (PC).

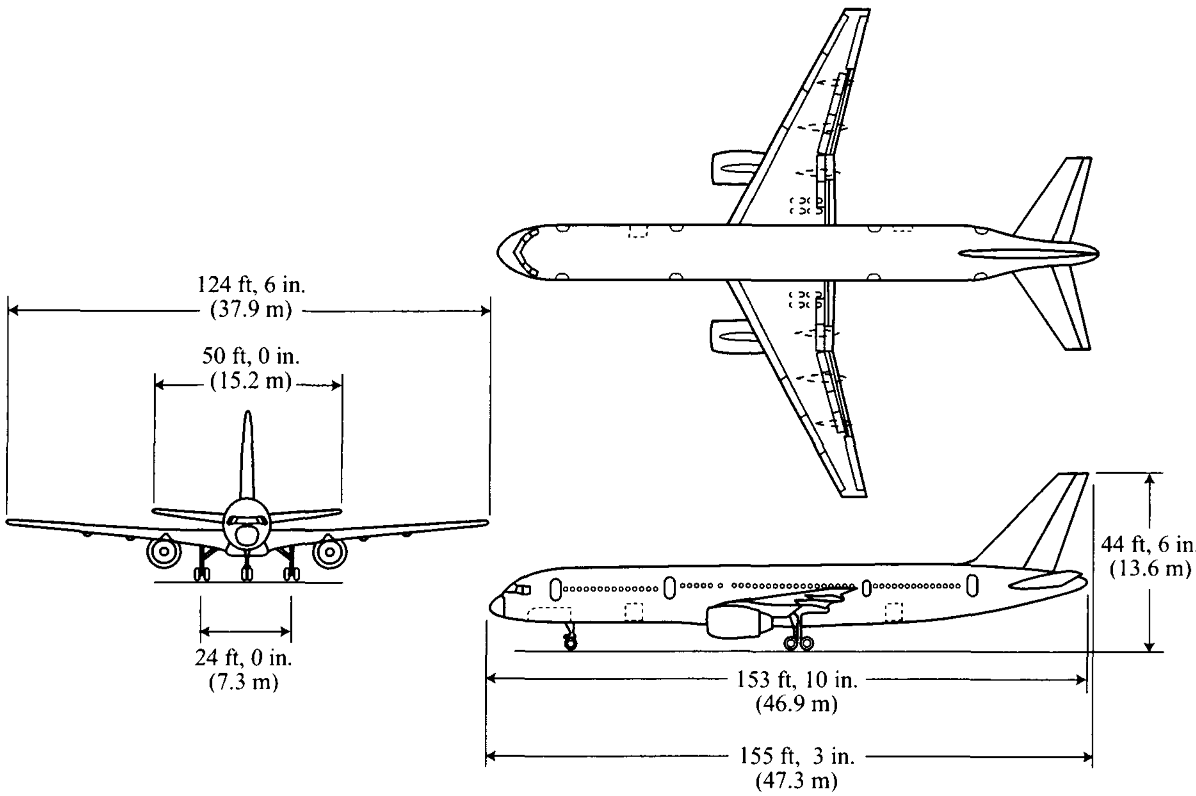


Figure 1. NASA LaRC ARIES B-757-200 aircraft.

Research Aircraft

ARIES is a Boeing 757-200 transport aircraft modified to conduct flight research for NASA Langley. The cabin area contains several pallets of experimental systems. These experimental systems include differentially corrected Global Positioning System (DGPS) capability, experimental HUD, video recording and distribution, and experimental computing systems. In addition, a technology transfer area (TTA) to demonstrate the concepts to onboard observers was available on ARIES.

The EP occupied the left seat in the Boeing 757. This position, with its associated displays and controls, was used for research testing and was known as the flight deck research station (FDRS). The safety pilot (SP) occupied the right seat. Research investigators were seated behind the flight crew in the cockpit jumpseats.

The GPS onboard ARIES received a differential correction signal via a very-high-frequency datalink from a ground station located at the airport. The accuracy of the DGPS was estimated to be within 10 ft. National Television Standards Committee format video was provided from several cameras located throughout ARIES. The pilot's forward field of view and tail cameras were recorded in super video home system (S-VHS) format. In addition, the SVS-RD and HUD imagery were also recorded in S-VHS format. The ARIES video distribution system was capable of distributing video imagery from many sources throughout the aircraft. Each pallet was capable of displaying any two video sources as selected by the pallet operator.

The technology transfer area (TTA) is an area near the aft end of the ARIES cabin and is primarily devoted to observation of the research being performed. The TTA featured two large 19-in. LCDs that could display distributed video imagery (however, the resolution of the imagery was degraded from that presented to the evaluation pilot). The 19-in. monitors were easily viewable from any of the 18 seats in the TTA. Use of the TTA included dedicated demonstration operations as well as observation areas for researchers.

The SGI® Onyx computer and SVS-GE were data linked via Shared Common Random Access Memory network (SCRAMnet). Except for pilot SVS-RD touch-screen inputs, all data provided to the SVS-GE research computers were provided via SCRAMnet.

Synthetic Vision Systems Research Display

The SVS-RD was designed to provide a large display area to replicate displays found in early generation glass cockpits, such as B-757s (size-A); larger size displays found in current generation glass cockpits, such as the B747-400 (size-D); and even larger display sizes envisioned for future aircraft (size-X). In addition to large size, the SVS-RD was required to be sunlight-readable, to have a resolution of approximately 90 pixels per inch (ppi), and to be removable in-flight to address safety-of-flight concerns. Sunlight-readable implies a display with a brightness of approximately 900 nits for applications in typical subsonic cockpits. Sunlight readability was particularly important during daytime checkout operations.

The SVS-RD was a commercial off-the-shelf 18.1-in. diagonal sunlight-readable display. The LCD panel was manufactured by Computer Dynamics and was repackaged by NASA for experimental use in the ARIES cockpit. Total viewing area of the display was 158.1 in. square. To take advantage of hardware graphics smoothing, the SVS-RD was operated in extended video graphics array (XVGA) mode (1024 × 768 pixels), yielding a vertical and horizontal resolution of 71 ppi. The SVS-RD weighed approximately 16 lb.

The SVS-RD was touch-screen equipped. Pilots used the touch screen to control FOV, symbology color, and the range of the map scale on the ND. The pilot could select the FOV in 5° increments or use a quick "jump-to" control for unity in 60°, 90°, and 120° FOVs. (Unity FOV was actually unity minification—the corresponding FOV was determined by the current display size and is discussed in a subsequent section.)

The SVS-RD was designed to be quickly removable (10 sec) in case of an in-flight emergency requiring access to the conventional B-757-200 displays. When in place, the SVS-RD did not obstruct the view of the back-up analog attitude direction indicator (ADI), airspeed (A/S), and altimeter instruments for either the EP or the SP.

The power supply for the SVS-RD was housed in a pallet in the cabin of ARIES. See figure 2 for a drawing of the SVS-RD that illustrates its placement on the ARIES instrument panel. See figure 3 for a photograph of the SVS-RD installation during the day, showing its relative placement and location with respect to other systems in the FDRS. See figure 4 for a photograph taken during night operations that illustrates the appearance of the SVS-RD during research operations.

Head-Up Display Device

The HUD system used for this evaluation was an experimental unit based on the Flight Dynamics Model 2300R head-up guidance system. The field of view of the HUD was approximately 30° horizontal

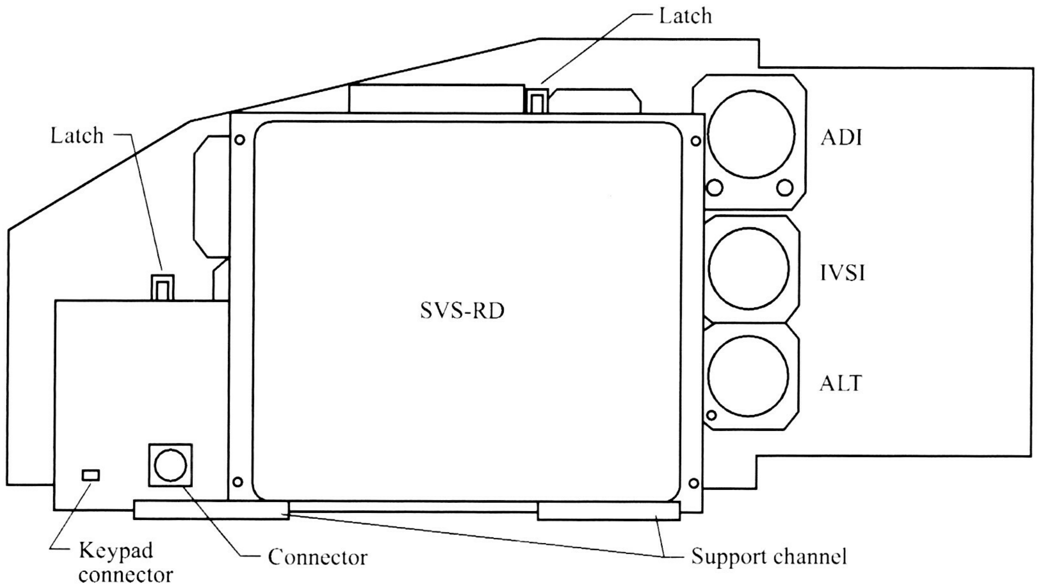


Figure 2. Front view drawing of SVS-RD installed in ARIES FDRS.

Figure 3. Photograph of SVS-RD installed in ARIES FDRS.

by 24° vertical, with a 4° look-down bias. A look-down bias sets the center of the HUD to be above the center of the displayed information to compensate for limited vertical FOV. Symbology and terrain information were displayed on the HUD via a raster-to-stroke converter unit. For this flight test, all symbology (including terrain) was displayed in raster mode. Maximum brightness of the HUD image was greater than 1000 ft-Lamberts and was continuously adjustable by the evaluation pilot. The HUD image contrast was also adjustable by the evaluation pilot. The evaluation pilot could view the HUD image when his eyes were within the design eye viewing volume of approximately 5 in. wide, 2.8 in. tall, and 6 in. deep. The design pilot's eye reference point (ERP) location was approximately 17 in. from the HUD combiner glass.

Figure 4. Photograph of SVS-RD taken during night approach.

Evaluation pilots could declutter the HUD via a button located on the top left handle of the control wheel. By repeatedly pressing the button, the evaluation pilot could sequence through three display states of the HUD. In the nominal state, both flight information symbology and terrain imagery were displayed on the HUD. The first press of the declutter toggle button removed the terrain imagery from the HUD (flight information symbology remained). A second press of the declutter toggle button removed the remaining flight information symbology (i.e., nothing was displayed on the HUD). A third press of the declutter toggle button returned the HUD to the nominal display state. The exact content and description of the symbology are included in a subsequent section.

SVS Graphics Engine

The SVS-GE was designed and integrated into ARIES to support specific research objectives that were beyond the capabilities of the existing ARIES SGI® Onyx computer. Primarily, research objectives requiring advanced computational capabilities involved the photo realistically textured terrain database concepts. At the time of this flight test, the SVS-GE consisted of state-of-the-art personal computer central processing units (PC CPUs), which were 700 MHz Intel® Pentium III CPUs, with state-of-the-art graphics cards (for PCs), which were the Intense 3D® Wildcat 4110s. The resulting dual-CPU work-station was a relatively low-cost, powerful computing system based on the Microsoft Windows NT® operating system (version 4, service pack 6).

In addition to cost, another advantage of using PCs was the large number of third party development tools available. The terrain databases were rendered using VTree® by CG2. Overlaying the terrain was HUD-type flight symbology (velocity vector, pitch ladder, and so on) created in-house using OpenGL® version 1.2. The software was developed by using Visual C++ (version 6.0 service pack 3).

The resulting system provided the capability to render the photo realistically textured, antialiased terrain database at approximately 20 to 30 Hz for fields of view up to 90° at XVGA resolution.

The SVS-GE was mounted in a pallet in the ARIES cabin. An operator at the pallet was able to control the display conditions presented to the evaluation pilot. Most of the required flight data were recorded via the SVS-GE at a rate of 10 Hz. In addition to data recorded using the SVS-GE, some pilot control input data were obtained using the ARIES data acquisition system.

Terrain Database

The Dallas/Fort Worth (DFW) Airport terrain database was generated using 1-arcsec (98-ft) resolution digital elevation model (DEM) data and covered an area of approximately 100 nmi by 100 nmi centered about DFW airport. Elevation accuracy of the data was approximately 3.2 ft. Terrain texturing was accomplished via two different processes: photo-realistic terrain texturing and generic terrain texturing based on elevation. The generically textured terrain database rendered the terrain color referenced to the absolute terrain height, with higher elevations receiving a lighter color.

Photo-realistic terrain texturing was created from ortho-rectified aerial photographs. The resulting scene was a realistic view, due to the photographic imagery employed, of the represented terrain. A disadvantage of the photo-realistic texture terrain database was the amount of texture memory necessary to create a realistic scene. The Wildcat 4110 graphics cards had 64 MB of texture memory. While this realistic scene generation required high-end computer graphics performance, currently beyond the capabilities of Federal Aviation Administration (FAA) certified computer platforms, the research system created for this test enabled achievement of all required research objectives. The advantage of the generically textured terrain is that less computational power is required to render it. Also, attributes such as color can be chosen to affect the appearance of the terrain.

Two levels of photo-realistic terrain texture were applied. High-resolution photo-realistic terrain texture was applied to an area 6 nmi by 15 nmi centered about DFW airport with the long axis aligned with runways 17C/35C. For this area, 3-m per pixel resolution ortho-rectified photographs were employed for the photo-realistic texturing. Due to cost considerations, the remaining DFW terrain database area was covered by 4-m per pixel ortho-rectified photographs.

All runways (including runway markings) and buildings at DFW were modeled using Multigen Creator®. The models were "planted" in the scene graph by using TerraVista®.

Display Configurations Evaluated

Symbology and Guidance

Refer to figures 5 through 10 for pictures of the various display concepts illustrating the symbology employed. Common symbology included for both head-up and PFD and EADI areas of the head-down display evaluations were a 5° increment pitch scale with reference waterline, roll scale with small tick marks every 5° and large tick marks every 10°, bank indicator with sideslip wedge and digital magnetic heading, wind speed and relative direction, heading scale with labels every 10° and tick marks every 5°, flight-path marker with acceleration along the flight-path indicator, reference airspeed error, and sideslip flag. Localizer and glide-slope course deviation indicators were also included. The localizer and glide-slope deviation indicators provided actual ship's information for the target runway (i.e.,

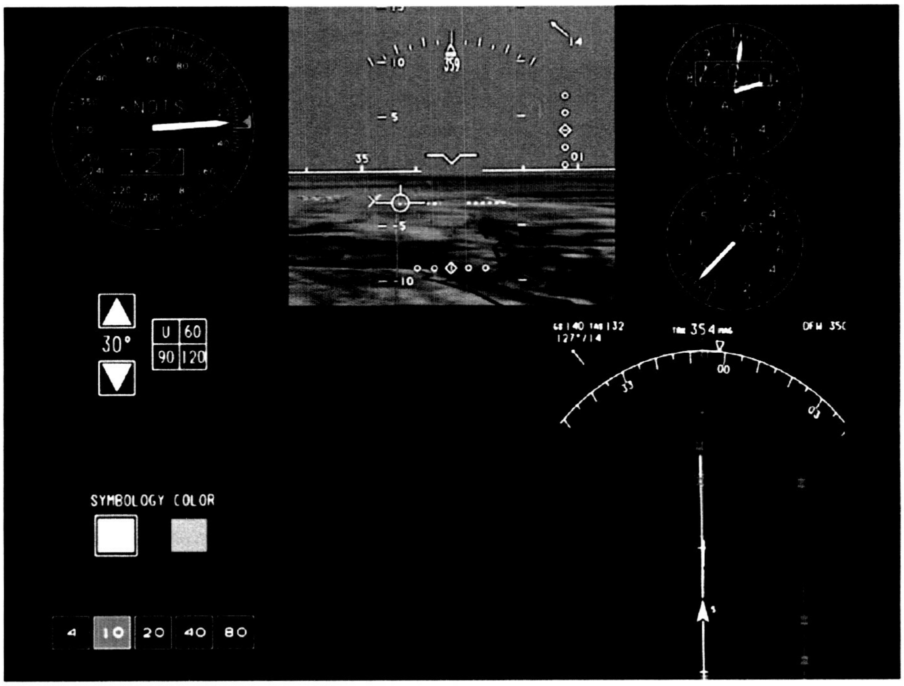


Figure 5. Image of size-A display for 30° FOV with generically textured terrain.

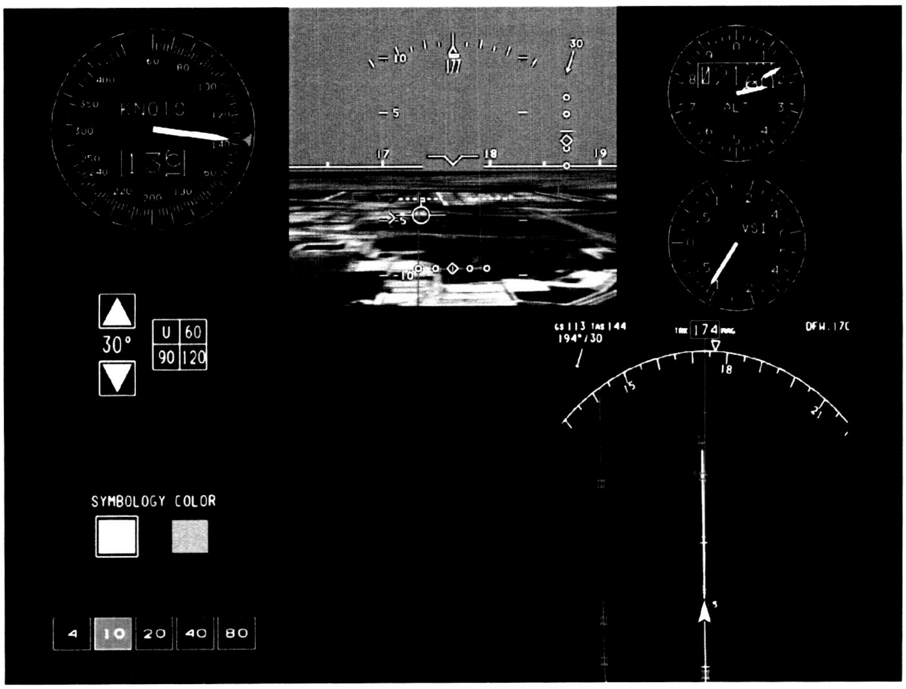


Figure 6. Image of size-A display for 30° FOV with photo-textured terrain.

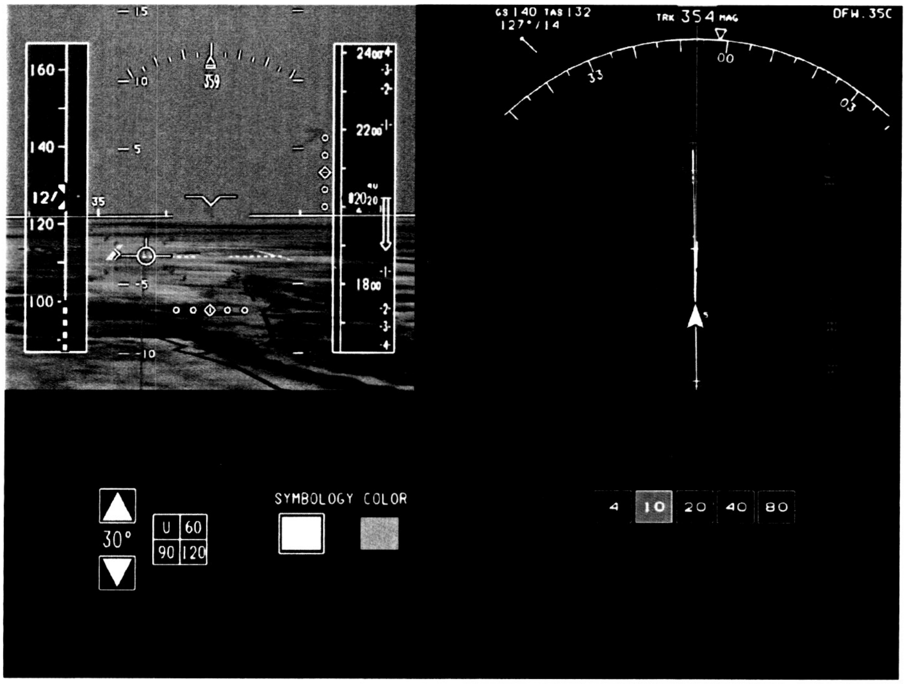


Figure 7. Image of size-D display for 30° FOV with generically textured terrain.

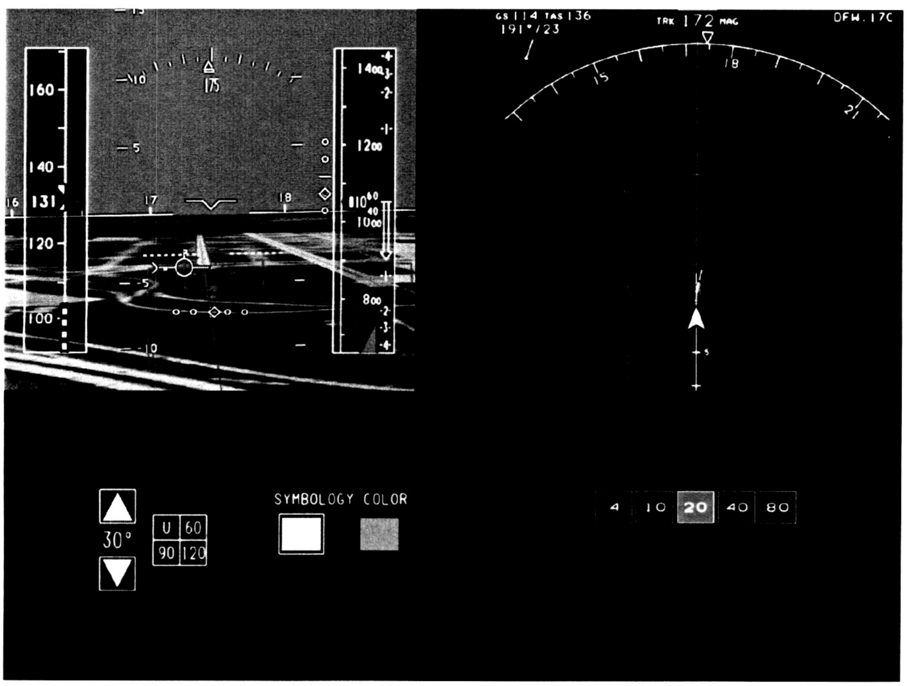


Figure 8. Image of size-D display for 30° FOV with photo-textured terrain.

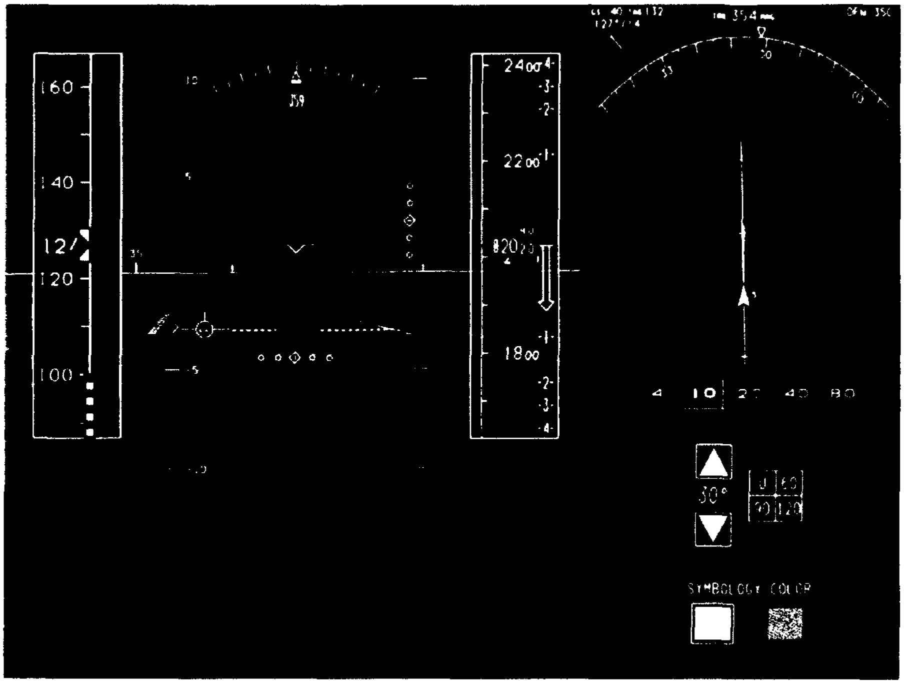


Figure 9. Image of size-X display for 30° FOV with generically textured terrain.

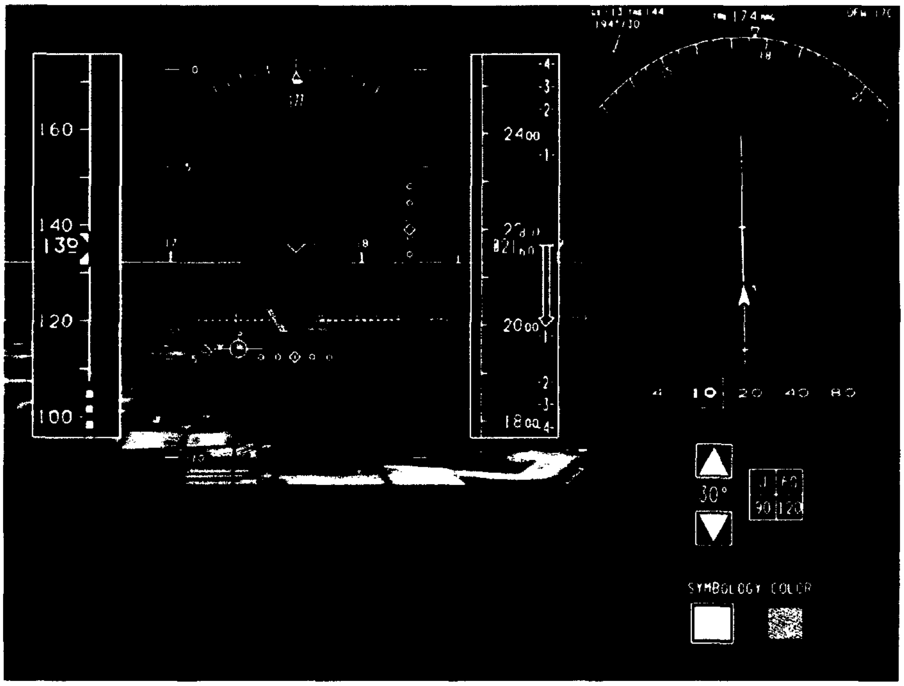


Figure 10. Image of size-X display for 30° FOV with photo-textured terrain.

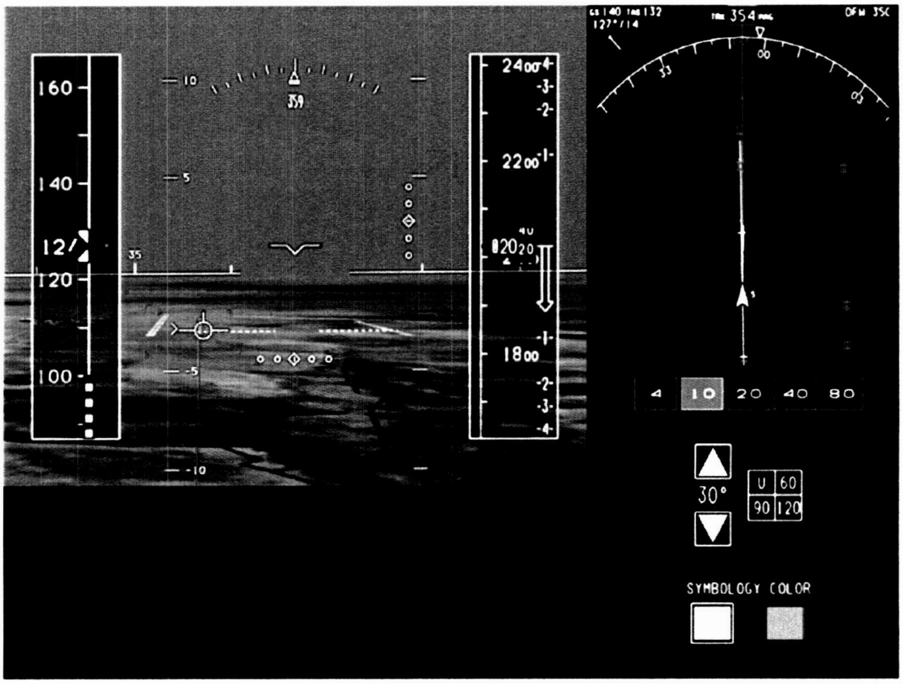


Figure 9. Image of size-X display for 30° FOV with generically textured terrain.

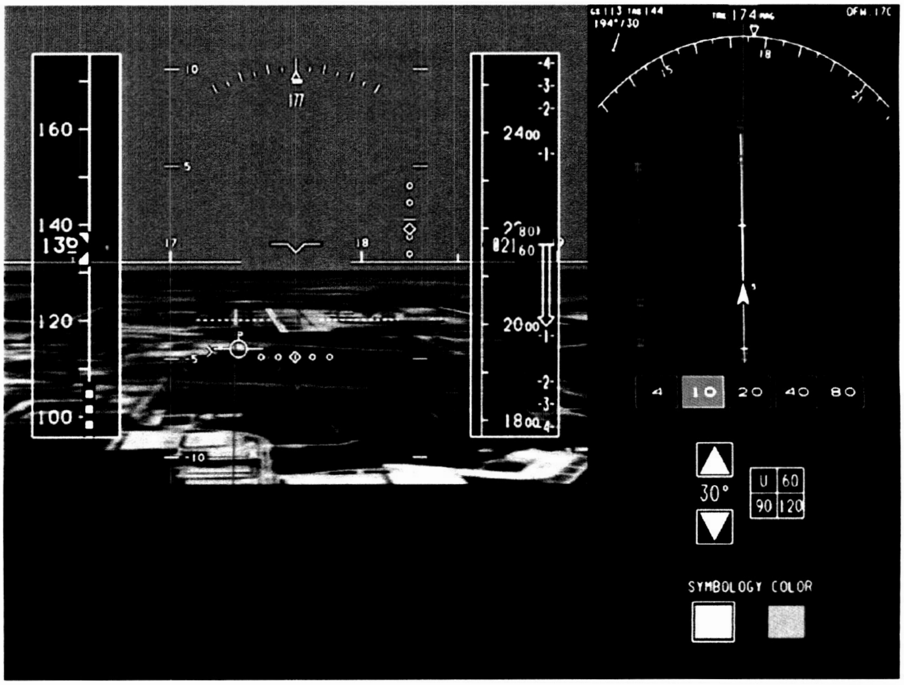


Figure 10. Image of size-X display for 30° FOV with photo-textured terrain.

runway 17C/35C) and were removed from the display if a valid signal was not received. In addition, a magenta runway outline box and extended runway centerline were included for the initial runway (i.e., runway 17L/35R). Target and initial runways are discussed in a subsequent section. All the common symbology was colored white on the HDD. Due to the monochrome nature of the HUD, all HUD symbology was green. The ND included the defined path and provided primary lateral navigation guidance prior to final approach.

For the size-D and size-X SVS PFDs, airspeed, altitude, and vertical speed were presented in a nominal tape format with airspeed bugs and limit speeds present. Traditional round dials were employed for airspeed, altitude, and vertical speed for the size-A display. No airspeed or altitude information was presented on the size-A EADI display area. Airspeed and altitude were displayed digitally for the SVS-HUD concepts. Airspeed, altitude, and vertical speed were colored white on the HDDs. Airspeed limits were shown to the pilot in standard red and white "barber pole" format.

Because some type of three-dimensional advanced guidance symbology is envisioned for production SVS displays, a minimal tunnel in the sky was incorporated into the symbology set for evaluation purposes. Intended to provide a three-dimensional representation of the intended flight path, the tunnel in the sky was presented to the evaluation pilots by magenta "crows feet" triads located at all four corners of the defined path. The dimensions of the minimal tunnel in the sky were based on the navigation performance of standard instrument landing systems (ILSs) and were 1 dot wide (limited to a maximum width of 600 ft), and 2 dots high (limited to a maximum height of 350 ft and a minimum height of 50 ft). Pilots were instructed to observe the tunnel in the sky but not to use it as a guidance system or perform closed-loop, high-gain maneuvering with respect to it. The primary purpose of the tunnel in the sky was to define where the three-dimensional path was.

Head-Down Display Concepts

Six HDD configurations were evaluated during this flight test. Three HDD formats were evaluated. The smallest format perspective SVS display, referred to as the size-A, replicates the instrument panel of a Boeing B-757-200. The next largest format HDD configuration was referred to as the size-D, which is representative of more modern aircraft, such as the Boeing B-777. The largest format HDD configuration was referred to as the size-X and extends potential SVS display technology to future aircraft applications with larger display surfaces. Dimensions of the HDD configurations are provided in table 1. Each type of HDD display is described in detail in the following sections. Each type of HDD configuration was evaluated with both generic-textured and photo-textured terrain database representations to create a total of 6 HDD configurations.

Table 1. Display Size and Available Fields of View and Minification Factors (MFs) for Evaluation

Size	Physical display dimensions		Unity FOV		MF			
	Width, in.	Height, in.	H, deg	V, deg	30°	60°	90°	120°
A	5.25	5	12.0	11.4	2.5	5.0	7.5	10.0
D	6.4	6.4	14.6	14.6	2.1	4.1	6.2	8.2
X	10	8	22.6	18.2	1.3	2.7	4.0	5.3

Size-A

The size-A display format was designed to replicate the basic instrument display package existing in early aircraft equipped with electronic displays, such as the B-757-200. See figures 5 and 6 for illustrations of the size-A display concept with generic and photo-textured terrain representations, respectively.

The size-A display format is best described as an EADI style of information presentation in that airspeed, altitude, and vertical speed are presented externally to the electronic display device. For this display format, airspeed, altitude, and vertical speed were displayed on the SVS-RD in traditional analog gauge format.

For the standard B-757-200, navigation information was provided to the pilot via the ND located directly below the EADI. Because the SVS-RD display surface was approximately 3.5 in. closer to the control wheel than the standard ship's displays, a significant portion of the lower center of the SVS-RD was obscured from the pilot's view. To provide adequate visibility of the ND for this flight test, the ND was moved to the right, as illustrated in figures 5 and 6. Information provided by the ND included ground speed, true airspeed, magnetic track, and selected approach route name digitally displayed at the top of the display. Distance along current track (green line with tick marks), the selected approach route and waypoints (magenta), and the current FOV employed on the EADI (dashed green lines emanating from the ownship symbol) were included on the moving map area of the display.

Size-D

The size-D display format was designed to replicate the basic instrument display package existing in current-generation aircraft equipped with electronic displays, such as the B-747. The electronic displays had a side-by-side presentation of an integrated PFD and ND. See figures 7 and 8 for illustrations of the size-D display format with generic and photo-textured terrain representations, respectively.

Size-X

The size-X display format expanded the size of the PFD portion of the display to the largest size available while retaining a size-B ND. In addition, the aspect ratio of the display was adjusted to be approximately 3:4, which had the benefit of raising the PFD to reduce the occlusion effect created by the wheel/column. See figures 9 and 10 for illustrations of the size-X display with generic and photo-textured terrain representations, respectively.

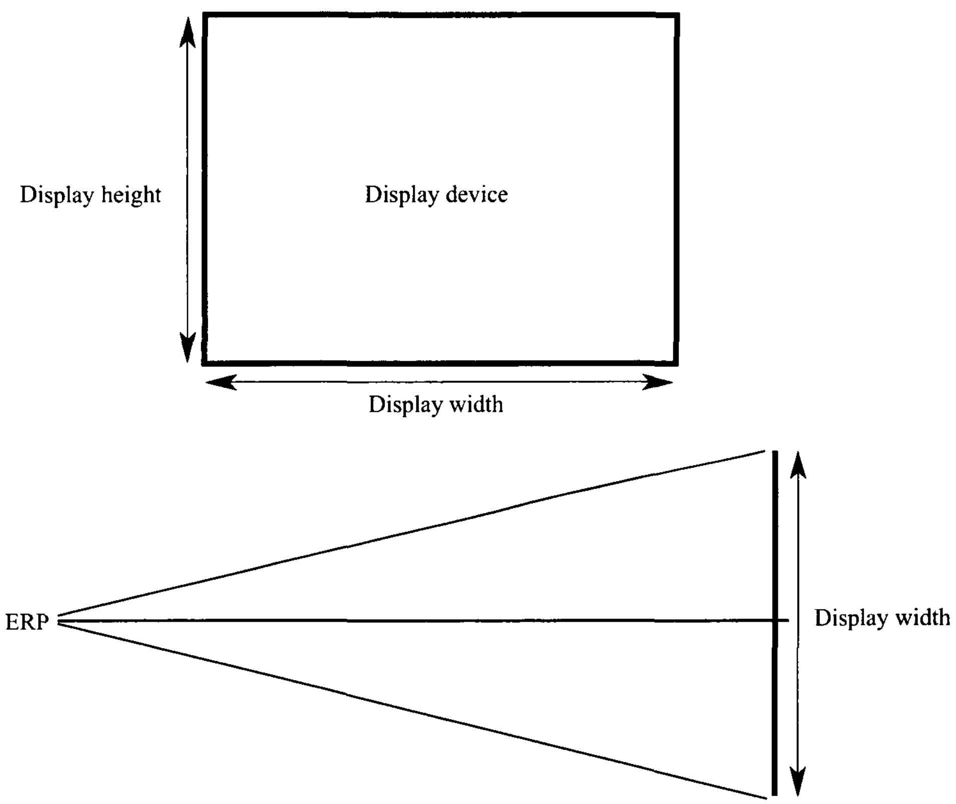
Discussion of FOV Issues

As previously stated, FOV is a design parameter that has specific importance for SVS displays. Larger FOVs permit pilots to view larger areas but require the display image to deviate from a conformal condition. Larger FOVs, while being useful during turns or in turbulence, make objects appear farther away (objects are minified). Variations in FOV affect the pilot's ability to judge distances. Lower FOVs provide an image that becomes more nearly conformal and enhances depth perception (objects are less minified). Objects that are narrow, like runways, become more visible with lower FOVs.

For an SVS image to be conformal, objects in the image need to subtend the same angles they do in the real world. Conformal SVS displays provide the size, shape, and location of the terrain to the pilot exactly as it would appear if the SVS display were a window. The conformal FOV of a display device is based on the size of the display device and the distance from the display device to the pilot's ERP. See figure 11 for a graphical illustration of these parameters, along with the equations for conformal horizontal and vertical FOV.

SVS imagery can be generated for almost any FOV and displayed to the pilot. The degree to which the SVS imagery deviates from the conformal FOV is referred to as the minification factor (MF). The MF is defined as the FOV of the imagery being displayed to the pilot, divided by the conformal FOV of the display device. The MF is also the inverse of the magnification factor. Conformal FOV is also referred to as unity magnification/minification.

Figures 12 and 13 present images for the SVS-PFD portion of the size-D display for 30° and 60° FOVs for identical aircraft positions, approximately 1.5 nmi from the runway. A MF of 2.1 resulted for the 30° FOV, while the 60° FOV produced a MF of 4.1 for this size display. From these two images, the effect of variations of the MF can be seen. Increased MFs create the illusion that objects (like the runway) are farther away as well as the appearance that the altitude is decreased. Another effect of variations of the MF is that lateral and vertical distance between the velocity vector and the runway has been reduced for increased MF. This effect can lead to variations in the pilot's ability to use the combination of the runway and the velocity vector as a guidance aid to manage flight path.



Conformal horizontal FOV = 2* inverse tangent (0.5*Display width/ERP)
Conformal vertical FOV = 2* inverse tangent (0.5*Display height/ERP)
Aspect ratio (AR) = Display height/Display width

Figure 11. Definition of conformal display's horizontal and vertical FOVs along with aspect ratio.

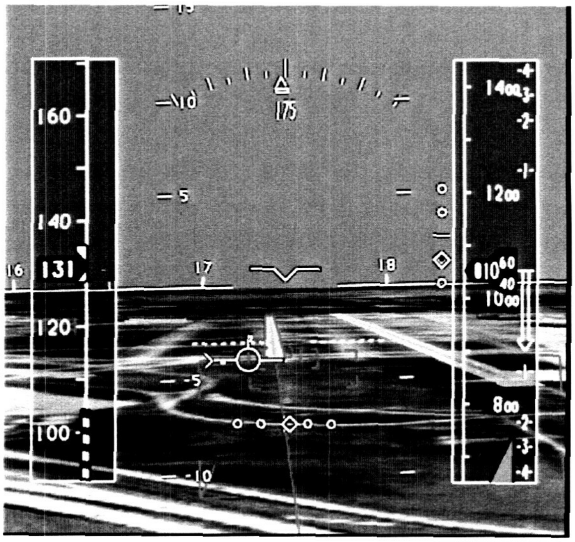


Figure 12. Image of size-D display for 30° FOV with photo-textured terrain (MF = 2.1).

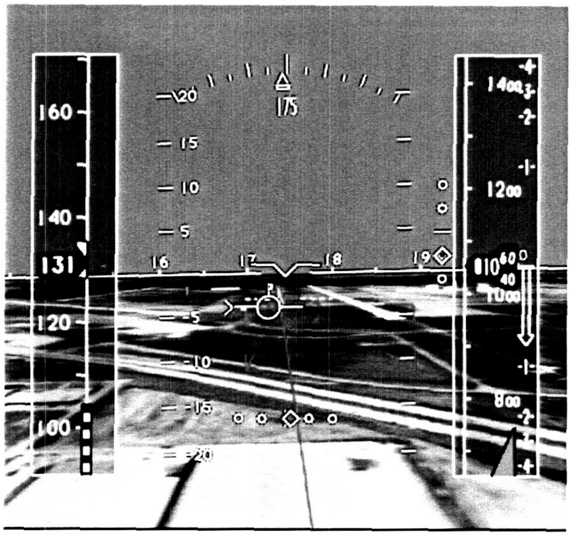


Figure 13. Image of size-D display for 60° FOV with photo-textured terrain (MF = 4.1).

Summary of Head-Down Display Sizes and Fields of View

For each HDD format (size-A, size-D, or size-X), the evaluation pilot was able to select the display field of view. Table 1 summarizes a sample of the FOVs tested. In table 1, unity FOV implies the FOV that would be provided by the display based on the size of the display area, combined with a 25-in. ERP distance (unity FOV was actually unity minification). During the flight test, the pilots were able to select desired FOVs in 5° increments or by using a quick "jump-to" pad with values of unity, 60°, 90°, and 120°. The selection was made via the touch-screen capability of the SVS-RD.

Head-Up Display Concepts

Two types of HUD configurations, generically textured and photo realistically textured terrain presentations, were evaluated during this flight test. In addition to terrain imagery, each HUD concept had flight symbology representative of current HUDs found in transport aircraft. The HUD imagery and symbology were conformal with the real world. Hence, the only FOV available to the pilot was at unity magnification/minification that subtended approximately 30° horizontal and 24° vertical. See figures 14 and 15 for illustrations of the HUD display concept with generic and photo-textured terrain representations, respectively.

Comparison of HDD and HUD Characteristics

There were major differences between the HUD and HDD concepts. These differences included, for the HUD, unity minification, the larger FOV at unity minification, collimation, and location, compared to the HDDs. Only minor differences in symbology were included in this test between HUD and HDD concepts. Symbology differences were limited to the method of presentation of altitude and airspeed. For the HUD concept, airspeed and altitude were presented digitally, whereas for the HDD concepts, airspeed and altitude were presented in analog round-dial or tape format.

All three HDDs tested were highly similar, with the primary difference between each display being limited to size. However, symbology varied slightly across the three HDDs tested. For the size-A display, airspeed, vertical speed, and altitude were presented on round dials, as opposed to integrated analog/digital "tape" presentations as employed for the size-D and size-X concepts. In general, various studies have been conducted that demonstrate similar results are obtained for both presentation styles. Reference 15 results indicate that while no differences were noted in airspeed or altitude tracking performance, subjective pilot comments suggested that there was lower workload for the integrated tape formats.

The symbologies used to present path error to the pilot were localizer and glide-slope course deviation indicators (CDIs) and the velocity vector. For SVS displays, the relationship between the velocity vector symbol and the runway image provided the pilot with flight-path guidance to augment information presented on the CDIs.

Test Matrix

Table 2 presents a summary of the NASA display conditions reported herein. While an avionics equipment vendor provided a display concept for ARIES DFW testing, data from those evaluations are not included in this report.

Evaluation Maneuvers

Four evaluation maneuvers were employed for the SVS DFW flight test. Two of the maneuvers, referred to as the nominal approaches, required the evaluation pilot to perform a downwind, base leg, and nominal final to either end of runway 17C/35C. The other two tasks, referred to as the runway change tasks, required the evaluation pilot to fly the same downwind path and initial base leg as for the nominal maneuvers; however, the base leg was shortened to establish an initial final approach to either runway 17L or 35R, depending on prevailing traffic flow at DFW. Then, when the aircraft was 5 nmi from the

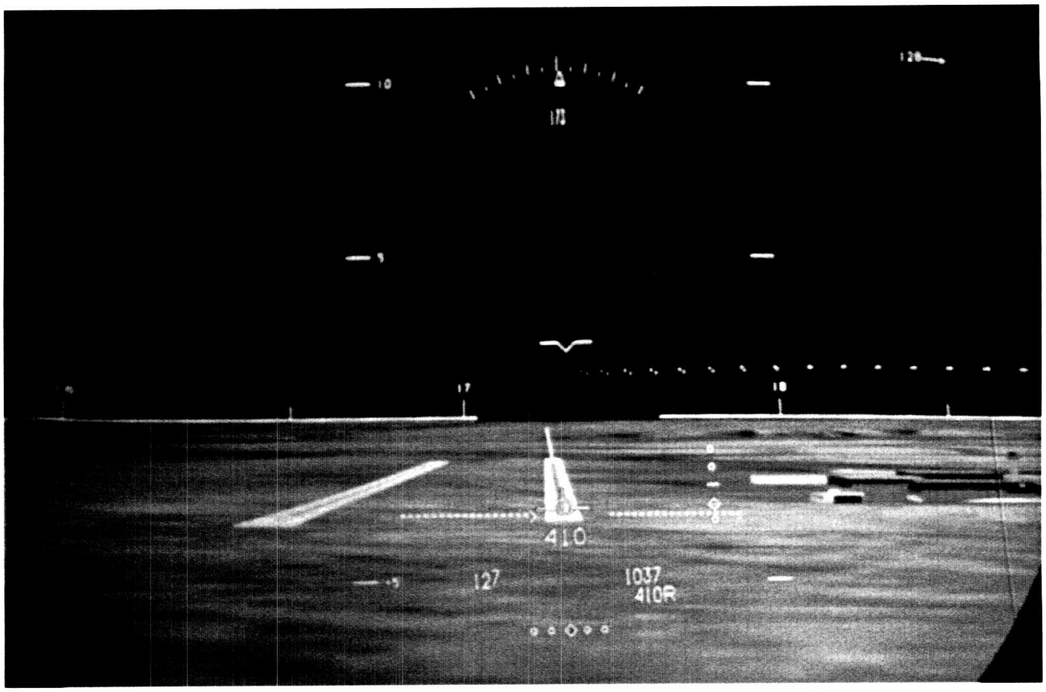


Figure 14. Image of generically textured HUD concept.

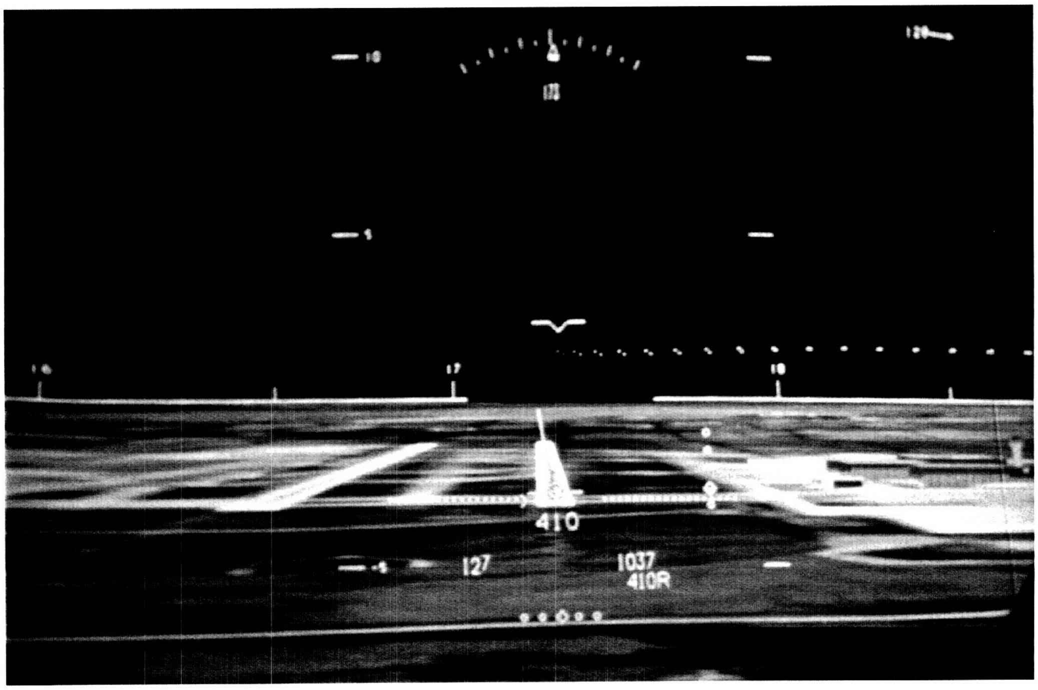


Figure 15. Image of photo realistically textured HUD concept.

Table 2. Summary of NASA Display Concepts Evaluated

Description	Generically textured (n)	Photo-realistically textured (n)
Size-A HDD	6	5
Size-D HDD	6	6
Size-X HDD	6	5
HUD with size-A generic HDD	7	5

initial runway, the pilots were instructed to execute a runway change maneuver to runway 17C/35C. The two nominal approaches were considered training and familiarization runs, while the runway change approaches were the primary task for the evaluations. All approaches included 3° glide slopes when appropriate.

The evaluation pilot assumed control of the aircraft abeam the mid-field position of runway 17C/35C at 5,000 ft above mean sea level (MSL) and at nominal approach airspeed. Just downwind of the mid-field position, the evaluation pilot began a descent to an altitude of 3,000 ft MSL following the tunnel in the sky. A turn-to-base leg was then performed by using the ND and tunnel-in-the-sky symbology on the display being evaluated. The evaluation pilot was required to maintain 3,000 ft MSL altitude during base leg. After completing the base-leg path, the pilot then executed a turn to establish the initial final approach. Flap settings were adjusted based on nominal B-757 operations. Pilots were instructed to use the auto throttles to maintain airspeed.

For the runway change tasks, the evaluation pilots were instructed to change to runway 17C/35C upon a call at 5 nmi from the runway 17L/35R threshold. Evaluation pilots were required to maneuver the aircraft with reference to the display being evaluated. Evaluation pilots were provided localizer and glide-slope information, but no other guidance information, for the target runway (17C/35C). See figures 16 and 17 for scale drawings of the flight paths employed for this test.

Evaluation Pilots

Six evaluation pilots participated in this experiment. Five of the six pilots were B-757 airline captains type-rated in the B-757 and landing current B-757 aircraft. The sixth pilot was the NASA project pilot who met the criteria of being type-rated and current in the B-757 aircraft. All the pilots had several thousand flight hours in various types of aircraft and had familiarity with HUDs. Being "landing current" in the aircraft required the pilots to perform 3 takeoffs and landing in the B-757 aircraft within the last 90 days.

Flight Test Procedures and Protocol

Pilot Briefings and Training

All pilots were briefed regarding the research objectives of the flight test, evaluation maneuvers, solicitation of pilot comments, subsequent data analysis efforts, and expected procedures immediately prior to each flight. Prior to the flight test, each pilot was trained on the evaluation maneuvers by using each display concept in a fixed-based, high-resolution graphics flight simulator at NASA LaRC.

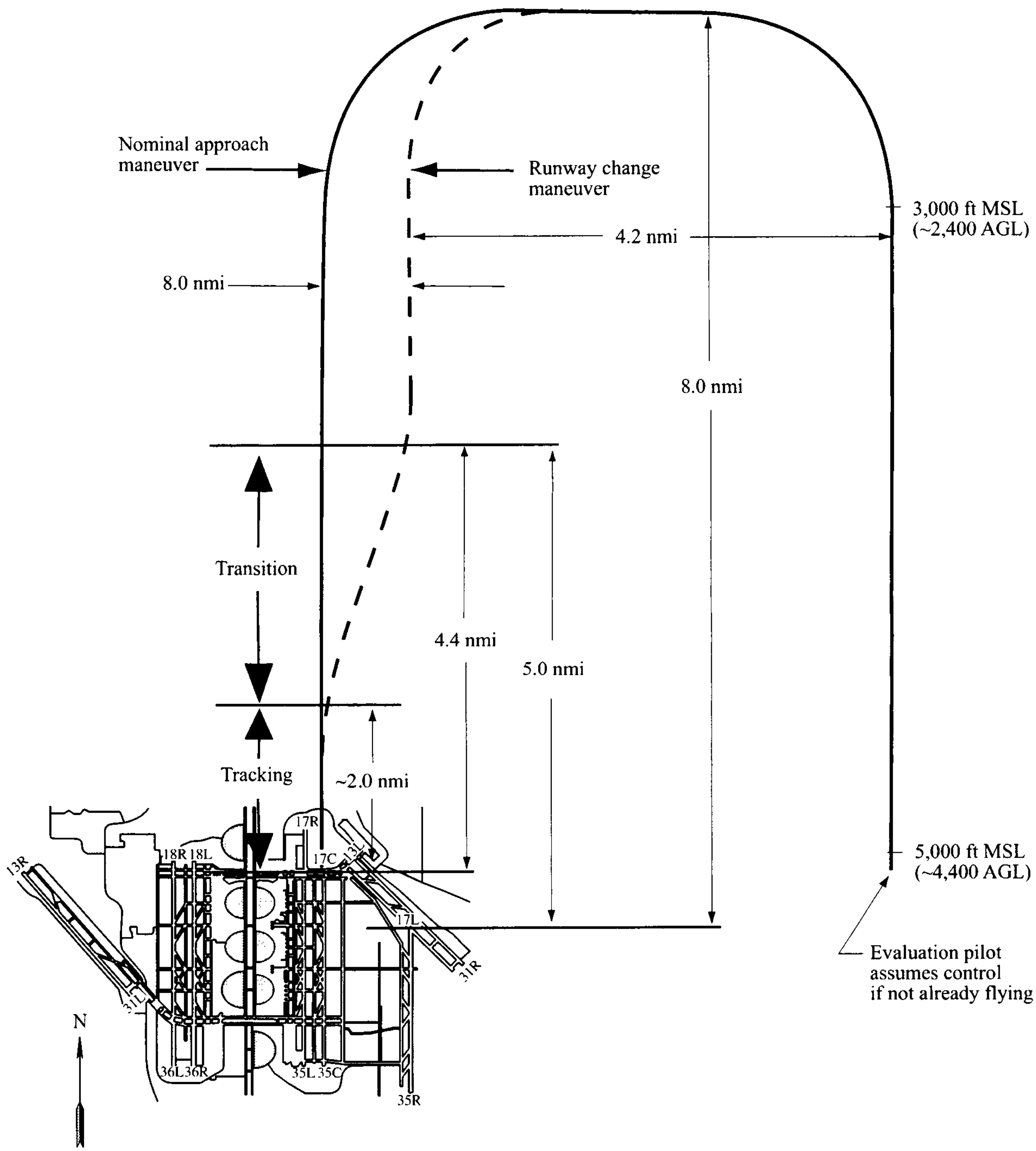


Figure 16. Illustration of flight path over ground for south-flow operations at DFW.

Pilot Comments

Qualitative pilot ratings and comments were collected during the flight and in post-flight debriefings. In-flight pilot comments were recorded via the videotape audio recording channel. A short in-flight questionnaire was provided to the evaluation pilot to elicit his comments after each run. In-flight comments were obtained between research maneuvers from the evaluation pilot once control was transferred to the safety pilot.

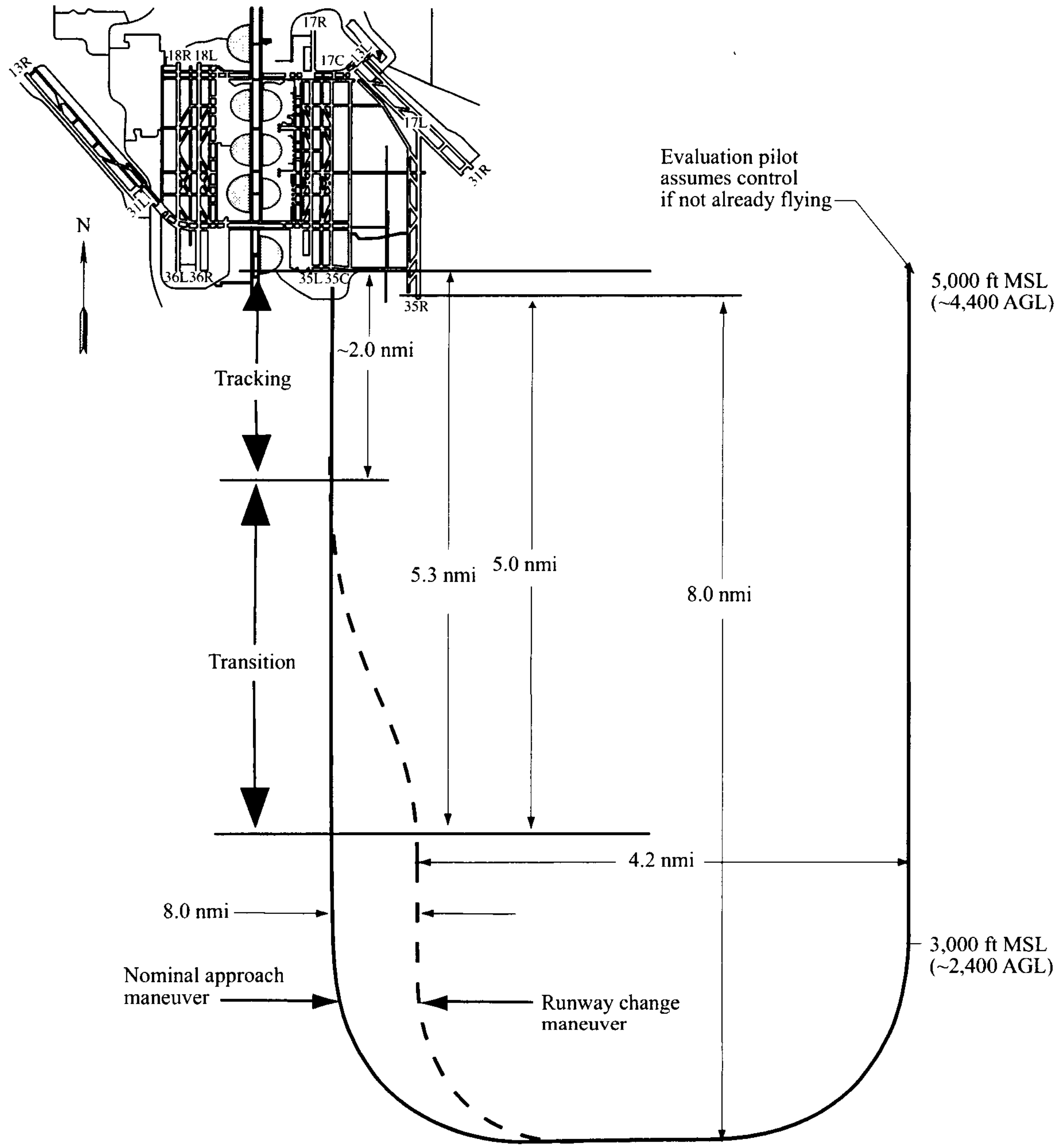


Figure 17. Illustration of flight path over ground for north-flow operations at DFW.

Post-flight qualitative pilot ratings and comments were obtained during extensive debriefings conducted immediately following each research flight. Flight test video was employed during debriefings to gather the most accurate comments and ratings possible. To maintain consistency during the post-flight debriefings, a debrief facilitator conducted all debriefings.

General Flight Test Operations

Evaluation pilots were briefed approximately 6 hours prior to flight time. Approximately 2 hours prior to flight time, the evaluation pilot, flight deck crew, and the balance of the aircraft crew boarded the

ARIES aircraft. The flight test director provided a final general briefing on the aircraft that covered the sequence of maneuvers to be performed and the anticipated general schedule.

After start-up checklists were completed, the evaluation pilot taxied the aircraft to the departure runway. Generally, the departure runway was either runway 35L or 17R. The safety pilot performed the takeoff. Once takeoff checklists were completed and the aircraft was established climbing in a low-workload condition, transfer of control of the aircraft to the evaluation pilot was accomplished. The evaluation pilot maneuvered the aircraft to the initial condition of the research run. The safety pilots interacted with air traffic control (ATC) and performed other communications.

Once established at the initial condition for a specific run, the evaluation pilot flew along the predetermined path. It should be noted that all segments of the maneuver were performed with reference only to the display being evaluated. Evaluation pilots were asked not to look out the window during the HDD evaluations and to adjust the brightness and contrast of the HUD to preclude seeing through the SVS imagery during HUD evaluations. The safety pilot manipulated flaps and landing gear positions based on commands from the evaluation pilot. Research maneuvers were terminated at 200 ft above ground level (AGL) and the evaluation pilot initiated the go-around. Once go-around checklists were completed and the aircraft established climbing in a low-workload condition, the safety pilot took control of the aircraft.

Conditions Tested

For this test, no imagery was displayed on the HUD during the HDD evaluations. However, the size-A HDD with generic texturing was employed for the HUD evaluations. The actual test conditions evaluated are presented in the following sections.

Entire Run List of Conditions Tested

Table 3 presents all research flight evaluations performed during this flight test. Conditions included are in the order presented to the evaluation pilot.

Order of Presentation of Display Conditions for NASA Display Concepts

Table 4 provides insight into the presentation order of the various display conditions flown by the six evaluation pilots. The numbers in this table refer to the order listed in table 3. The experiment was arranged by display type so that analyses of results could compare one HDD size against any other. The terrain-texturing condition was often retained for two successive runs to facilitate the execution of the flight test since some additional time was required to switch between those conditions. The two nominal approaches with the NASA HUD and size-A generically textured terrain concepts, always performed first, were considered training and familiarization runs.

Due to the capricious nature of the flight testing, combined with a very high desire to obtain HUD data, evaluation pilots always evaluated the NASA Opaque HUD concept first, followed by the vendor HDD evaluations during the first 2 hours of the test session. Once the vendor HDD concept evaluations were completed, an approximately 1-hour break was performed, with the aircraft parked at a convenient location near the research runway. After the break, evaluations of the NASA HDD concepts were conducted during the next 2 hours of the test session. Vendor HDD evaluations included either two or

Table 3. Research Flight Maneuvers Performed at DFW

Pilot number	Display configuration	Task	Order
1	Photo-HUD with Generic-A HDD	Nominal RWY 17C	1
1	Generic-HUD with Generic-A HDD	Nominal RWY 17C	2
1	Generic-HUD with Generic-A HDD	RWY Change 17L to 17C	3
1	Photo-HUD with Generic-A HDD	RWY Change 17L to 17C	4
1	Vendor HDD	Vendor Long to RWY 17C	5
1	Vendor HDD	Vendor Short to RWY 17C	6
1	Vendor HDD	Vendor RWY Change 17L to 17C	7
1	Generic-A HDD	RWY Change 17L to 17C	8
1	Photo-A HDD	RWY Change 17L to 17C	9
1	Photo-D HDD	RWY Change 17L to 17C	10
1	Generic-D HDD	RWY Change 17L to 17C	11
1	Generic-X HDD	RWY Change 17L to 17C	12
1	Photo-X HDD (only monitored)	RWY Change 17L to 17C	13
2	Photo-HUD with Generic-A HDD	Nominal RWY 35C	1
2	Generic-HUD with Generic-A HDD	Nominal RWY 35C	2
2	Generic-HUD with Generic-A HDD	RWY Change 35R to 35C	3
2	Photo-HUD with Generic-A HDD	RWY Change 35R to 35C	4
2	Vendor HDD	Vendor RWY Change 35R to 35C	5
2	Vendor HDD	Vendor Short to RWY 35C	6
2	Generic-X HDD	RWY Change 35R to 35C	7
2	Photo-X HDD	RWY Change 35R to 35C	8
2	Photo-D HDD	RWY Change 35R to 35C	9
2	Generic-D HDD	RWY Change 35R to 35C	10
2	Generic-A HDD	RWY Change 35R to 35C	11
3	Photo-HUD with Generic-A HDD	Nominal RWY 35C	1
3	Generic-HUD with Generic-A HDD	Nominal RWY 35C	2
3	Photo-HUD with Generic-A HDD	RWY Change 35R to 35C	3
3	Generic-HUD with Generic-A HDD	RWY Change 35R to 35C	4
3	Vendor HDD	Vendor RWY Change 35R to 35C	5
3	Vendor HDD	Vendor Short to RWY 35C	6
3	Photo-A HDD	RWY Change 35R to 35C	7
3	Generic-A HDD	RWY Change 35R to 35C	8
3	Generic-X HDD	RWY Change 35R to 35C	9
3	Photo-X HDD	RWY Change 35R to 35C	10
3	Photo-D HDD	RWY Change 35R to 35C	11
3	Generic-D HDD	RWY Change 35R to 35C	12

Table 3. Concluded

Pilot number	Display configuration	Task	Order
4	Photo-HUD with Generic-A HDD	Nominal RWY 35C	1
4	Generic-HUD with Generic-A HDD	Nominal RWY 35C	2
4	Generic-HUD with Generic-A HDD	RWY Change 35R to 35C	3
4	Photo-HUD with Generic-A HDD	RWY Change 35R to 35C	4
4	Vendor HDD	Vendor RWY Change 35R to 35C	5
4	Vendor HDD	Vendor Short to RWY 35C	6
4	Photo-D HDD	RWY Change 35R to 35C	7
4	Generic-D HDD	RWY Change 35R to 35C	8
4	Generic-A HDD	RWY Change 35R to 35C	9
4	Photo-A HDD	RWY Change 35R to 35C	10
4	Photo-X HDD	RWY Change 35R to 35C	11
4	Generic-X HDD	RWY Change 35R to 35C	12
4	Vendor HDD	Vendor Long to RWY 17C	13
5	Photo-HUD with Generic-A HDD	Nominal RWY 17C	1
5	Generic-HUD with Generic-A HDD	Nominal RWY 17C	2
5	Generic-HUD with Generic-A HDD	RWY Change 17L to 17C	3
5	Photo-HUD with Generic-A HDD	RWY Change 17L to 17C	4
5	Vendor HDD	Vendor RWY Change 17L to 17C	5
5	Vendor HDD	Vendor Short to RWY 17C	6
5	Vendor HDD	Vendor Long to RWY 17C	7
5	Generic-D HDD	RWY Change 17L to 17C	8
5	Photo-D HDD	RWY Change 17L to 17C	9
5	Photo-X HDD	RWY Change 17L to 17C	10
5	Generic-X HDD	RWY Change 17L to 17C	11
5	Generic-A HDD	RWY Change 17L to 17C	12
5	Photo-A HDD	RWY Change 17L to 17C	13
6	Photo-HUD with Generic-A HDD	Nominal RWY 17C	1
6	Generic-HUD with Generic-A HDD	Nominal RWY 17C	2
6	Generic-HUD with Generic-A HDD	RWY Change 17L to 17C	3
6	Photo-HUD with Generic-A HDD	RWY Change 17L to 17C	4
6	Vendor HDD	Vendor Long to RWY 17C	5
6	Vendor HDD	Vendor Short to RWY 17C	6
6	Vendor HDD	Vendor RWY Change 17L to 17C	7
6	Photo-X HDD	RWY Change 17L to 17C	8
6	Generic-X HDD	RWY Change 17L to 17C	9
6	Generic-A HDD	RWY Change 17L to 17C	10
6	Photo-A HDD	RWY Change 17L to 17C	11
6	Photo-D HDD	RWY Change 17L to 17C	12
6	Generic-D HDD	RWY Change 17L to 17C	13

Table 4. Presentation Order of Display Concepts

Display configuration	Pilot 1	Pilot 2	Pilot 3	Pilot 4	Pilot 5	Pilot 6
Generic-A HDD	8	11	8	9	12	10
Photo-A HDD	9		7	10	13	11
Generic-D HDD	11	10	12	8	8	13
Photo-D HDD	10	9	11	7	9	12
Generic-X HDD	12	7	9	12	11	9
Photo-X HDD	13	8	10	11	10	8
Generic-HUD with Generic-A HDD	3	3	4	3	3	3
Photo-HUD with Generic-A HDD	4	4	3	4	4	4

three approaches after the HUD evaluations. Additional evaluations of the vendor HDDs were performed if time permitted at the end of the test session.

Data Analysis

Qualitative

Pilots were asked to respond to a brief, inter-run questionnaire during the course of the experiment after each run. The list of questions presented to the pilot after each run can be found in appendix A. The pilot provided open-answer responses to inter-run questions in his own words. Pilots were also encouraged to provide a running commentary during the flight, if they were able to do so. In-flight pilot comments were subsequently transcribed and are also included in appendix A.

A formal post-flight debriefing was conducted after each flight in which pilots were asked to select response options to a battery of questions. Interspersed in the formal questionnaire were sections to provide comments. All questions employed for the formal post-flight questionnaire are included in appendix B. Post-flight questionnaire data and pilot comments are included in appendix C.

Quantitative

The analyses conducted for the quantitative data involved statistical evaluations of the data for the runway change maneuver, beginning when the aircraft was established on final approach 5 nmi from the initial runway and terminated at the go-around point. Analyses were performed for two separate segments of the runway change maneuver. One segment of the runway change maneuver, referred to as the transition segment, began at 5 nmi from the initial runway threshold and ended when the pilot had established the aircraft onto the final approach path for the new target runway. The other segment, referred to as the tracking segment, began at that point and ended at 200 ft AGL (the go-around point). See figures 16 and 17 for an illustration of the runway change maneuver for north- and south-flow operations.

During the transition segment, large-amplitude flight-path corrections were applied by the pilot to maneuver the aircraft to the target final approach path. During the tracking segment, small-amplitude flight-path corrections (typical of the tracking task) were applied. Separation of the maneuver into two segments provided a more detailed investigation of the data and more consistent control of the statistical variability of the dependent variables than a single segment analysis could have provided. To separate the data into transition and tracking segments, the following criteria were employed: (1) aircraft position had to be within ±1 dot of localizer and glide-slope error, (2) ground track error had to be within ±5°, and (3) the flight-path angle error had to be within ±3°. Note that a nominal 3° glide slope was employed for all final approach segments. Also, the distance along the extended runway centerline from the initial runway threshold was employed for these analyses because runway 17C/35C had displaced thresholds with respect to runway 17L/35R. The threshold for the target runway was 4.4 nmi from the aircraft at the point where the runway change was initiated for approaches to runway 17C, compared to 5.3 nmi for approaches conducted to runway 35C. See figures 16 and 17 for illustrations of the relationship between the two runway pairs.

Metrics that came from both segments included minimum, maximum, and mean FOVs; average MF for the HDDs; and root mean square (RMS) values for pilot's wheel, column, and rudder pedal control inputs. For the transition segment, the maximum intercept angle, the maximum heading change, and the minimum, maximum, and average bank angles were calculated. For the tracking segment, RMS values of linear lateral and vertical flight-path error were calculated, as well as RMS values of localizer and glide-slope error.

In addition, measures to characterize the separation point of the transition and tracking segments were also identified. These measures at the segment transition point included the altitude above ground level and the distance along the extended runway centerlines from initial and target runway thresholds.

The data collected in this experiment were analyzed by using univariate analyses of variance for each metric. Student-Newman-Keuls tests (at a 5-percent significance level) of individual means were performed at various stages in the analyses.

Results and Discussion

Results from this flight test are presented for qualitative and quantitative data. Qualitative results, such as pilot comments, numerical ratings, and so on, are presented in the summary of the qualitative pilot ratings section. Analyses of pilot performance data are presented in the summary of quantitative pilot performance section.

Summary of Qualitative Pilot Ratings and Comments

Pilots provided comments regarding various aspects of the displays evaluated during this study. Verbal pilot comments are provided in appendix A. All written pilot comments that were recorded are included in appendix C. This section summarizes appendices A and C. Common themes and similar comments made by most, or all pilots are included in this section. In addition, pilot ratings and comments considered highly insightful or especially meaningful are also included. Ratings for situation and spatial awareness are examples of especially meaningful pilot responses.

Qualitative Results Regarding Spatial and Situation Awareness

Pilot ratings indicated that as the HDD size increased, maintaining spatial awareness, situation awareness, and predicting flight path became easier (see figs. 18–20). For most pilots, ratings also indicated that they could more easily interpret aircraft parameters such as airspeed, altitude, and vertical speed as the synthetic PFD size increased. These subjective ratings correlated well with pilot comments recorded

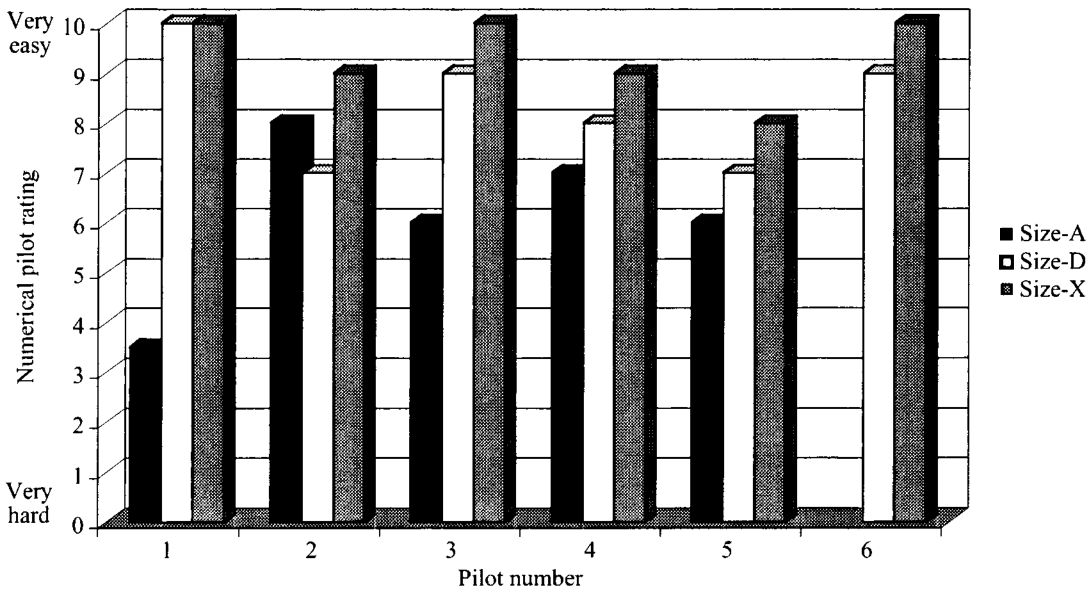


Figure 18. Response to question 8: Evaluate this display for maintaining spatial awareness while flying the approach.

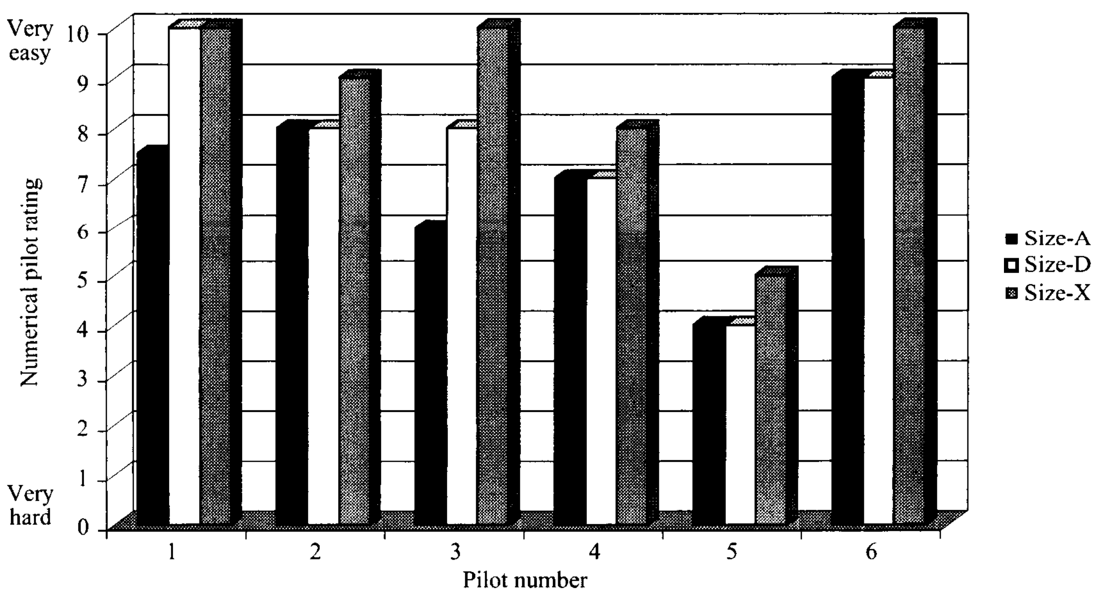


Figure 19. Response to question 9: Evaluate ease of maintaining situation awareness.

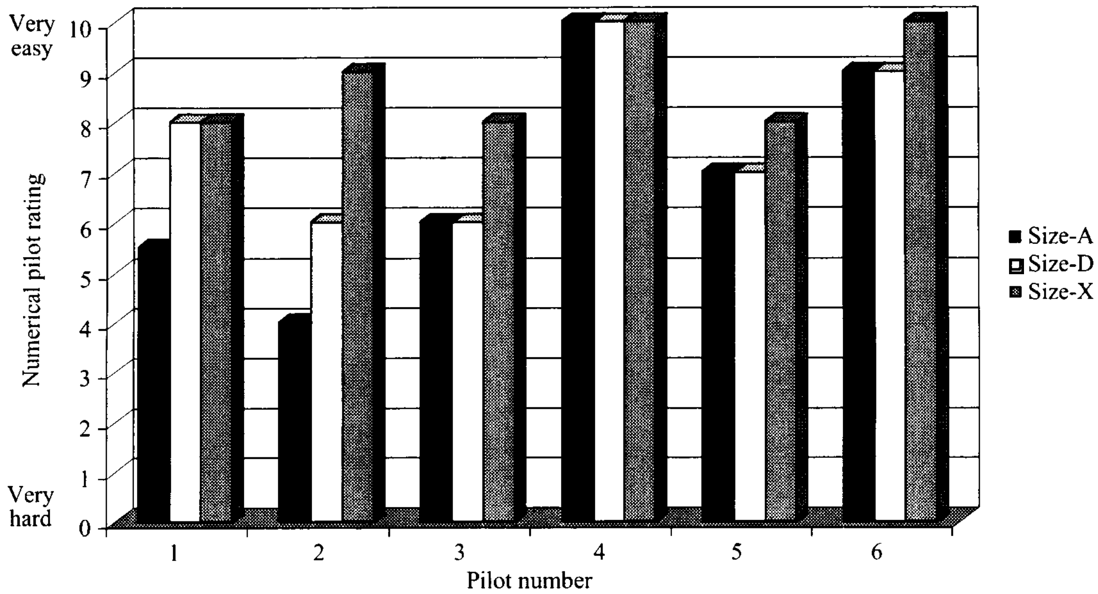


Figure 20. Response to question 7: Evaluate ease of predicting flight path.

during the flights and in the questionnaires. For the HDD concepts tested (size-A, -D, -X), all pilots liked the largest display best because of the increased display space that made it easier to decipher objects and terrain and allowed for more precise flying. All pilots felt that synthetic vision information could effectively be presented on the size-D and size-X primary flight displays. All but one pilot felt that the size-A HDD, with selectable FOV, could effectively display synthetic vision information. Most pilots felt that the size-A HDD would have provided better situation awareness in a terrain-challenged airport, a black hole approach, or in instrument meteorological conditions (IMC) than a conventional HDD.

Qualitative Results Regarding FOV

All pilots felt that a single FOV would not be the best solution and would impose undue restrictions on display effectiveness. Pilot comments indicated an increasing desire to be able to clearly see what was directly in front of the aircraft during the latter stages of final approach. Pilots recommended multiple FOVs based on phase of flight, such as en route, approach, etc. Lower FOVs (lower MFs) were recommended for the final approach segment of approximately 20° to 30°. Pilots felt that larger FOVs would be useful for en route phases of flight to be able to see airborne hazards and into turns. One pilot felt the size-A was too small to be useful, even with a selectable FOV option. Many of the pilots commented that unity FOV on the size-A display could not be used except for short final because the velocity vector and terrain were near or completely off the bottom of the display. (A potential solution to this problem would be to offset the center of the displayed information from the actual display surface center, as is done with HUDs.)

Pilots were asked to specify their first and second choice of FOVs if they could only select two for each of the HDDs evaluated (see table C.3 in appendix C). Analysis of variance (ANOVA) on the two pilot-preferred FOV choices, with display size as the independent variable, showed no significant effects for display size for choice one or choice two. This result indicates that pilots selected FOVs for the given task and did not consider MFs to a significant degree. Figure 21 presents the means of the pilot-preferred FOV choices for each display size. Pilots generally wanted to be able to select between approximately 30° and 60°.

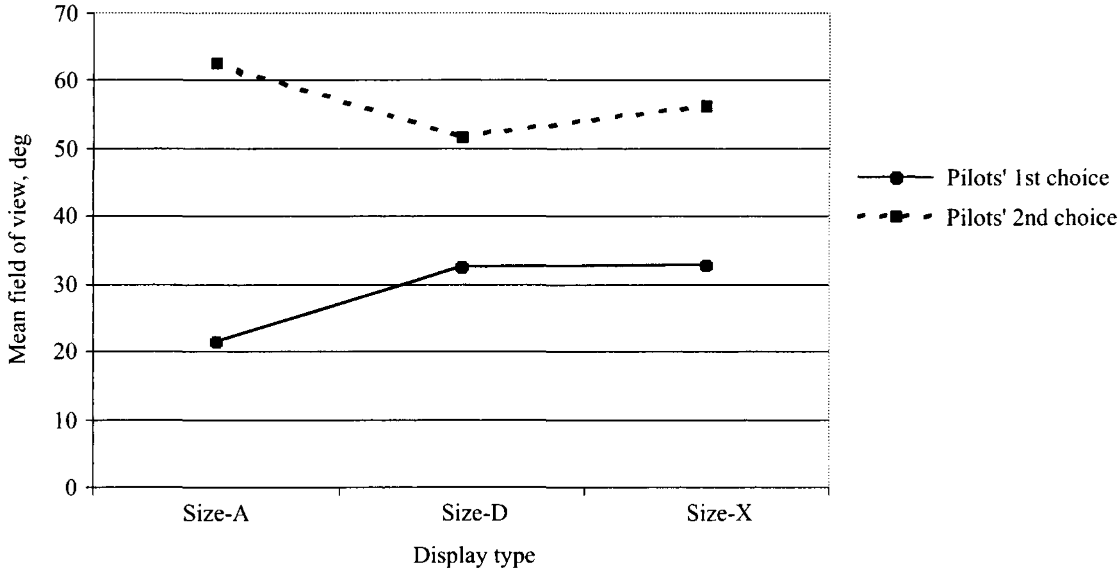


Figure 21. Means of pilot-preferred choices for FOV.

Regarding control of HDD FOV, all of the pilots found the touch-screen mechanization for FOV selection awkward. All pilots indicated that providing only a few specific FOV choices would be better and stressed that the ability to move between the various choices should be made extremely easy, with the selected FOV being obvious. An overwhelming majority of the pilots (all but one) recommended an exclusively manual control technique for FOV selection. The pilot with the differing opinion suggested an automatic function with a manual override capability.

Qualitative Results Regarding Terrain-Texturing Methods

In general, pilot ratings indicated that it was easier to use a head-down primary flight display with photo-realistic terrain texturing than one with generic terrain texturing (see fig. 22). This trend was also seen in the pilot ratings for the HUD texturing type in that photo-realistic terrain texturing was generally preferred over generic terrain texturing (see fig. 23). These subjective ratings correlated well with pilot comments recorded during the flights and in the questionnaires. Four of the six pilots felt it was easier to determine relative position and judge depth perception with the photo-realistic terrain texturing than with the generic texturing for both the HDD and the HUD concepts. One pilot stated that neither texturing type enabled him to judge depth, range, or altitude cues very well but did assist him in acquiring the new runway during runway change tasks. Another pilot was only able to marginally judge depth, range, and altitude cues with the photo-realistic terrain textured database when in unity FOV. This pilot's ability to judge these cues was even more marginal with the generically textured database when in unity FOV. Some of the evaluation pilots were very familiar with the DFW area and they indicated that the information included in the photo realistically textured terrain databases, such as shopping malls, roads, and population areas was useful.

Other interesting comments regarding the type of terrain texturing were (1) for the head-down concepts, the level of detail in the photo-realistic textured terrain database enabled the pilot to line up the aircraft with the new runway during runway changes, helped determine the rate of closure with objects over the ground, and supplied cueing for runway centerline alignment; (2) it was felt that the generically

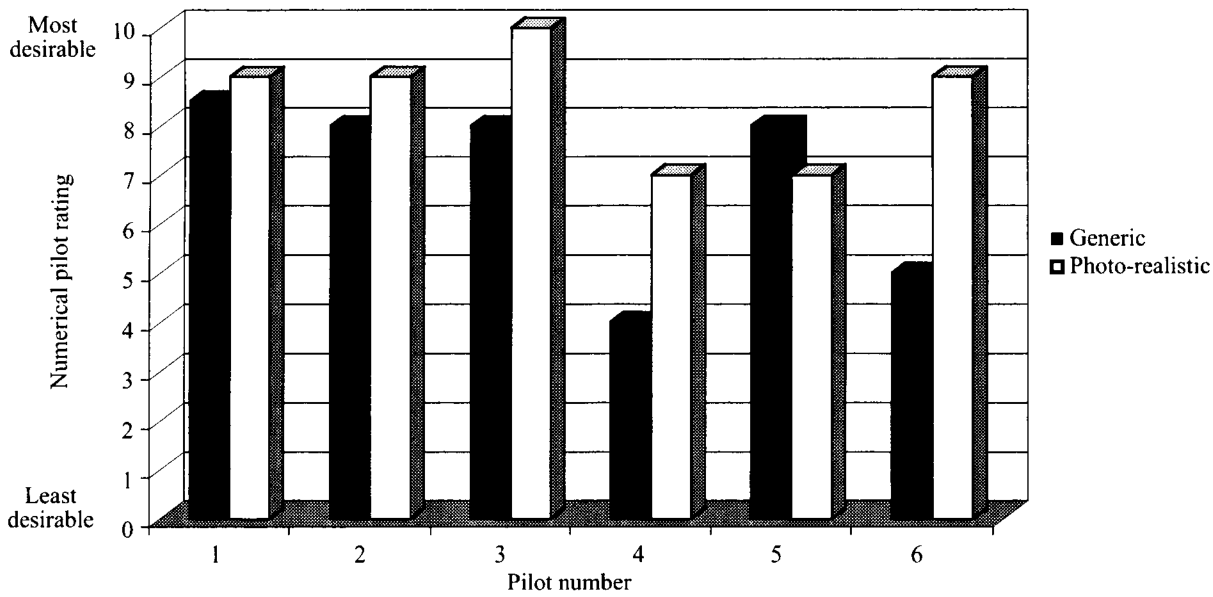


Figure 22. Response to questions 16 and 17: Please evaluate ease of using primary flight display with generic and photo-realistic texturing.

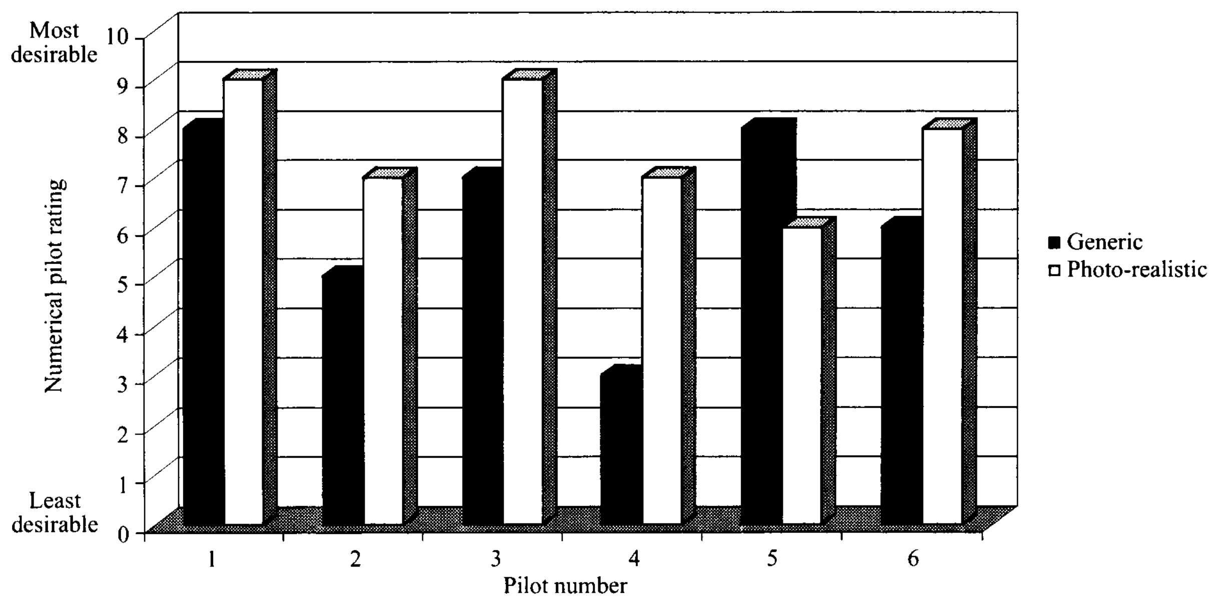


Figure 23. Response to questions 18 and 19: Based on your exposure to different HUD concepts, please indicate your overall relative ranking/grading of generically and photo realistically textured HUD concepts.

textured terrain database might be better for nonterminal operations because the level of detail of the photo-realistic database may not be useful; (3) the generic database appeared less cluttered because the airport and runway features stood out better against the background; and (4) the photo-realistic textured terrain database on the HUD provided a comfort factor to the pilot because of the ability to overlay synthetic terrain and objects on the real world.

Qualitative Results Regarding SVS HUD Concepts

Although not specifically queried, half the evaluation pilots stated that they preferred the HUD to the HDD concepts. Reasons cited for this preference were that the HUD has a wider FOV (at unity minification), enables the pilot's head to be in a natural position to land (head up, eyes out), and has all the information a pilot needs in one area. Improvements that pilots would like to see on the HUD include the addition of color symbology, a vertical speed indicator, objects in the database with which the pilot can verify position (e.g., waypoints found on the navigation display represented in the HUD symbology), and an automatic see-through capability when the real world becomes visible on the HUD. The other half of the pilots did not make any substantial comments regarding preference of HDD versus HUD SVS applications.

Summary of Quantitative Pilot Performance

Analyses of the flight data were performed for each of the display concepts evaluated with the runway change task. A tabular listing of the data for the performance measures analyzed can be found in appendix D. While most of the ensuing discussions center on statistically significant results, there are some instances where observations are presented without statistical verification. In most cases, however, results are not presented unless statistical significance was obtained (e.g., none of the pilot control activity measures yielded statistically significant results). The two nominal approaches with the NASA HUD and size-A generically textured terrain concepts, always performed first, were considered training and familiarization runs and were not included in the analysis.

Effect of Display Size or Type, Terrain-Texturing Method, and Runway Assignment on Segment Transition Point

Figures 24 and 25 present linear lateral error from the target runway centerline for all runway change maneuvers for the size-A, size-D, and size-X HDDs as a function of distance to the target runway threshold. Figure 25 presents linear vertical error from the target runway glide slope for all runway change maneuvers for the size-A, size-D, and size-X HDD displays. Figure 26 presents linear lateral error from the target centerline as a function of distance to the target runway threshold and linear vertical error from the target runway glide slope as a function of distance to the target runway glide slope antenna location for the HUD displays. In figures 24 through 26, the segment transition points are indicated by the squares with dots. Table 5 presents the mean and standard deviation of the distance of the segment transition point from the original runway threshold.

An ANOVA conducted on the dependence of the segment transition point from the initial runway threshold as a function of display size or type, texture method, and runway pair showed no significant differences for the main effects or the interaction effects between the main factors. In general, pilots were able to re-establish the aircraft onto the new final approach approximately 2.6 nmi from the initial runway threshold at an altitude of approximately 790 ft AGL. These results were probably obtained because pilots employed approximately 42° FOV for all HDDs, permitting a similar intercept angle while

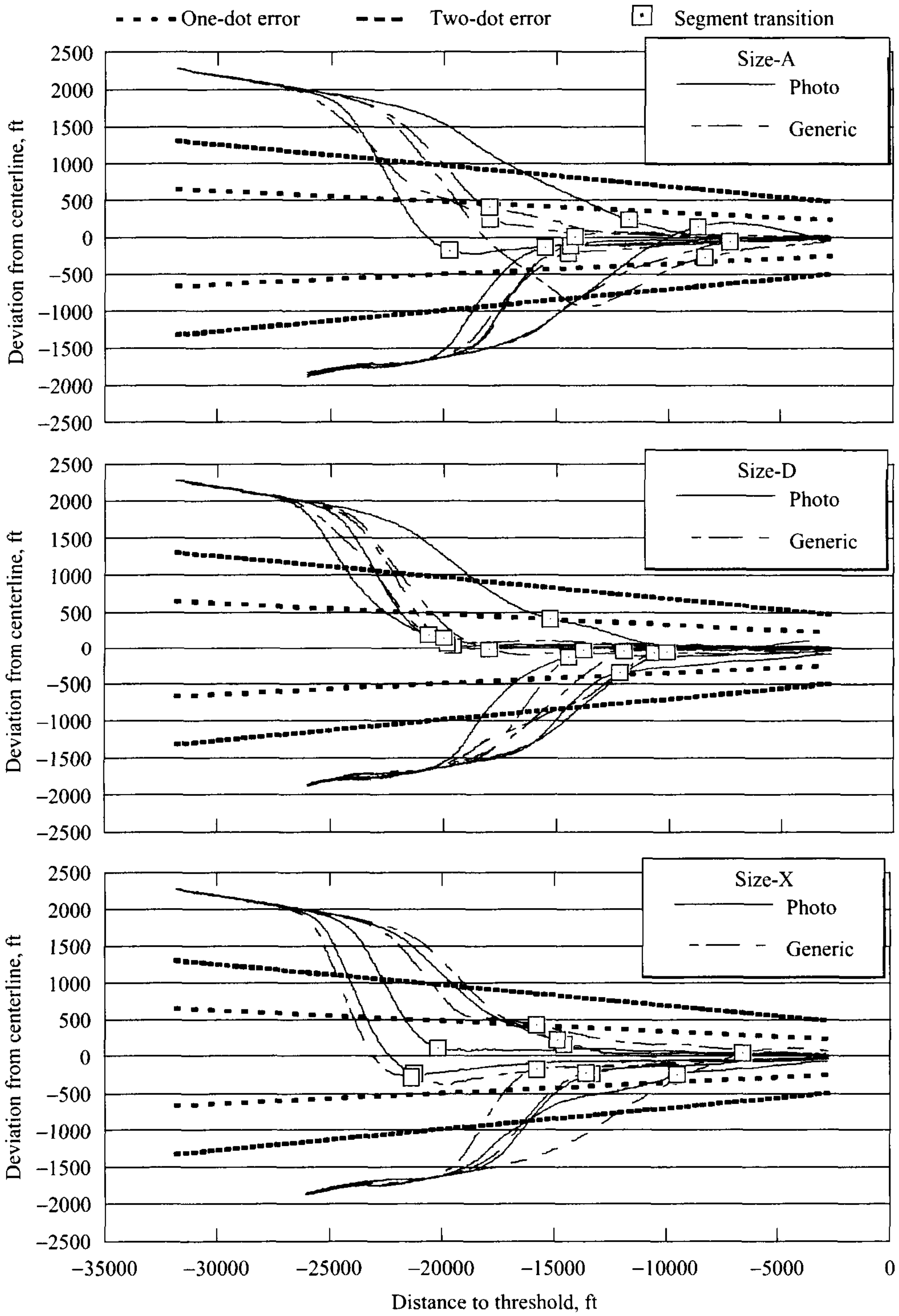


Figure 24. Lateral deviation from target runway centerline as function of distance to target runway threshold for size-A, size-D, and size-X HDD.

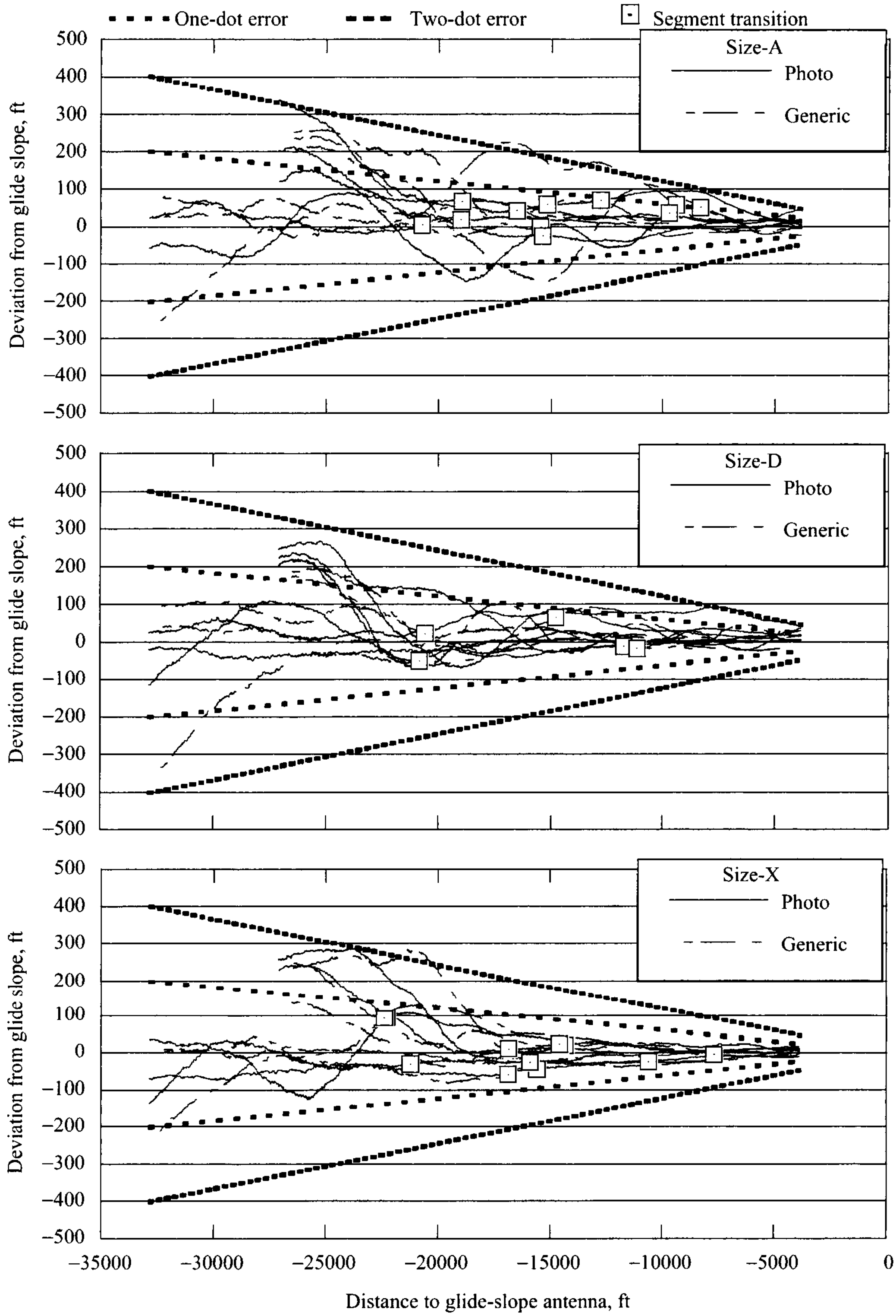


Figure 25. Vertical deviation from target runway glide slope as function of distance to target glide-slope antenna for size-A, size-D, and size-X HDD.

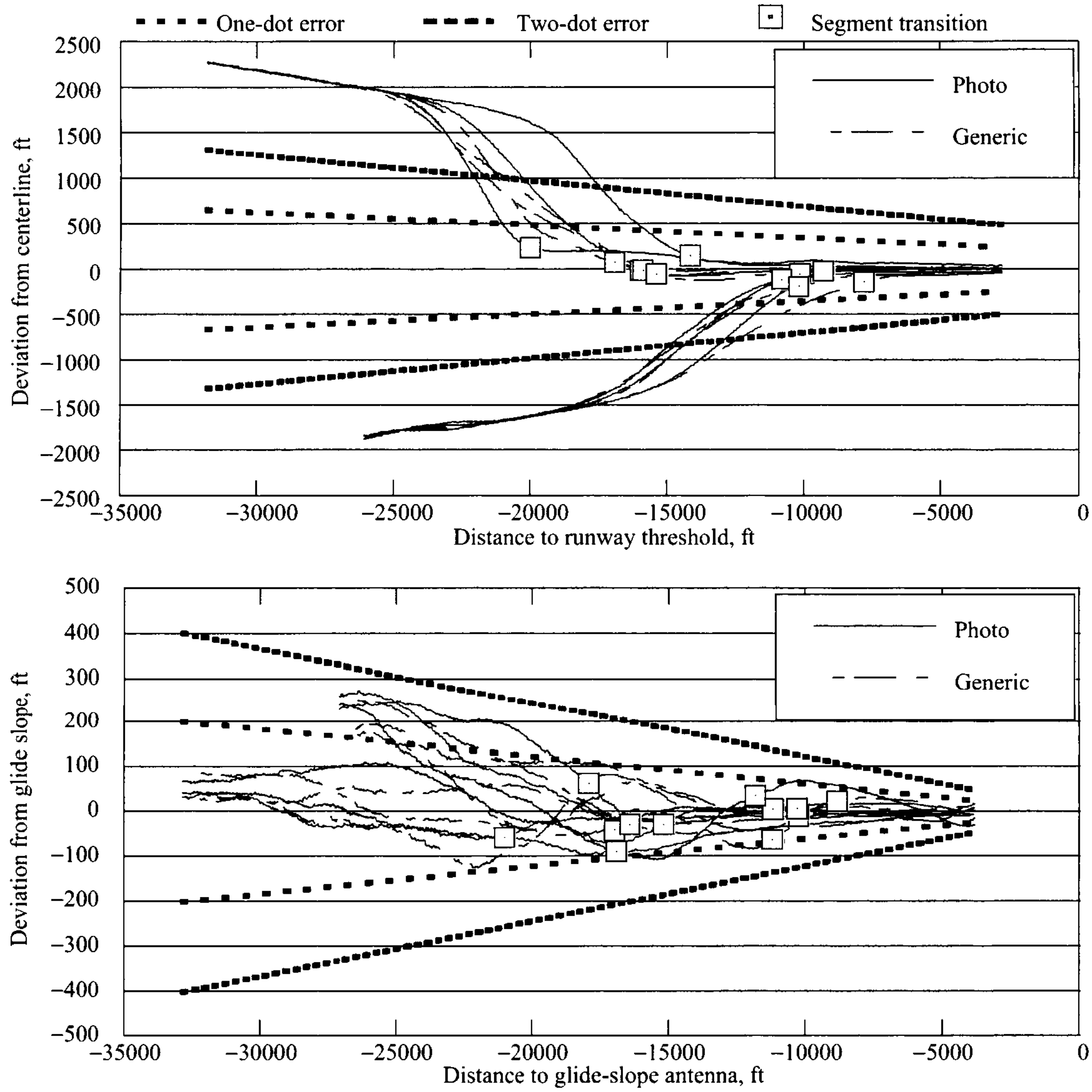


Figure 26. Lateral deviation from target runway centerline (as a function of distance to the runway threshold) and vertical deviation from target runway glide slope as function of distance to target glide-slope antenna for HUD.

retaining a view of the new runway on the SVS display. However, it can be seen in table 5 that the mean segment transition point for the HUDs was a little worse (closer to the runway threshold) than the HDDs (although not statistically significant). This result may be attributed to the fact that the FOVs selected for the HDDs were larger than the 30° FOV of the HUD.

The quantitative result that pilots performed similarly for the generic and photo-realistic terrain-texturing concepts is in contrast to pilot comments received. Four of the six pilots felt it was easier to determine relative position and judge depth perception with the photo-realistic texturing than with the generic texturing for both the HDD and the HUD concepts. Pilot comments also indicated that photo realistically textured terrain facilitated the lineup of the aircraft with the new runway during runway changes, helped determine the rate of closure with objects over the ground, and supplied cueing for runway centerline alignment.

Table 5. Segment Transition Point Distance From Threshold

Terrain texturing	Display size or type	Mean, nmi	Stdev, nmi	Number of samples
Generic	Size-A	−2.4	0.8	6
	Size-D	−2.8	0.2	6
	Size-X	−2.6	0.6	6
	HUD	−2.3	0.2	7
	Average	−2.6	0.5	25
Photo-realistic	Size-A	−2.6	0.7	5
	Size-D	−2.8	0.4	6
	Size-X	−2.7	0.5	5
	HUD	−2.4	0.3	5
	Average	−2.6	0.5	21
Total	Size-A	−2.5	0.7	11
	Size-D	−2.8	0.3	12
	Size-X	−2.7	0.5	11
	HUD	−2.4	0.3	12
	Average	−2.6	0.5	46

Due to the large amount of pilot variability in the transition segment of the runway change maneuver, relatively low number of data points, and variability of weather effects, statistically significant results were not obtained for the segment transition point. However, it is interesting to note the statistics for the segment transition point for the size-A concepts. Since the size-A was smaller than the other HDDs, combined with a similar FOV employed for all HDDs, a higher MF was created for the size-A display. The larger MF for the size-A display is believed to be the cause of the somewhat oscillatory nature of the vertical error, as exhibited in figure 25, which resulted in a large standard deviation of the segment transition points. (A homogeneity of variance test was not significant, either.) Also note that the data provided in table 5 are the distance along the original runway centerline from the threshold of the initial runway. Smaller negative numbers are indicative of poorer performance.

Effect of Display Size or Type on Localizer Tracking

Statistical analyses of the flight-path control performance data (RMS values of lateral path error) were performed. An ANOVA on the RMS lateral flight-path error during the tracking segment, with display size or type of display (i.e., HUD or size-A, size-D, size-X) and terrain texture as independent variables, showed a significant main effect for display type ($F(3,38) = 3.68$, $p \leq .020$), but no significant main effect for texture method or interaction effects between the two main factors. Figure 27 presents RMS linear lateral error results for the display size and type factor for the tracking phase. See table 6 for a summary of these data. Pilots were able to achieve better performance indicated by lower localizer tracking error for the HUD concepts than with the HDD concepts. In addition, pilots were generally able to demonstrate more consistent results for the HUD concepts as indicated by the lower standard deviations. (A homogeneity of variance test showed no significant effect, however.)

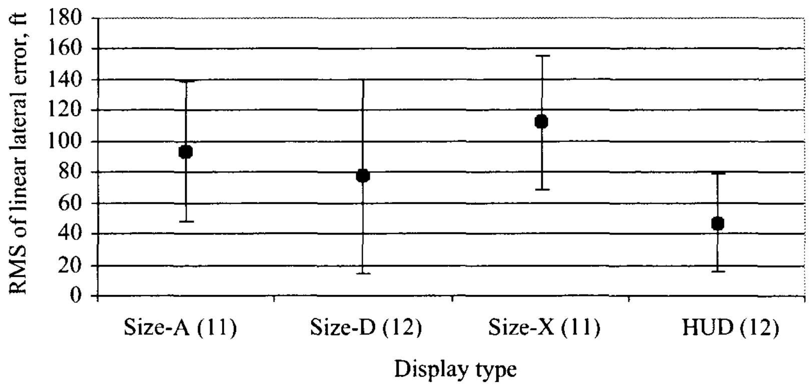


Figure 27. RMS values of linear lateral error for SVS display concepts evaluated during tracking phase.

Table 6. RMS Linear Lateral Error for Tracking Phase

Terrain texturing	Display size or type	Mean, ft	Stdev, ft	Number of samples
Generic	Size-A	93.5	57.2	6
	Size-D	46.1	19.1	6
	Size-X	121.7	57.4	6
	HUD	43.1	28.1	6
	Total	76.1	53.1	24
Photo-realistic	Size-A	92.2	36.9	5
	Size-D	104.2	73.5	6
	Size-X	102.1	38.9	5
	HUD	55.5	37.5	6
	Total	91.6	55.6	21
Total	Size-A	92.9	46.7	11
	Size-D	75.1	59.5	12
	Size-X	112.8	48.5	11
	HUD	49.3	32.2	12
	Total	81.5	51.8	46

A graphical inspection of the linear lateral error for the tracking phase for the different size HDDs and HUDs (see figs. 24 and 26) support the statistical analysis in this area. However, if consideration is given to the entire runway change maneuver, rather than to just the tracking portion after the segment transition point, linear lateral error for the size-A display generally indicates a more oscillatory nature with substantial overshoots and undershoots of the target localizer. As HDD size increases (size-D and size-X) the nature of the linear lateral error changes substantially, with an elimination of overshoots and a substantial reduction in undershoots, although no significant effect was indicated in the statistical analysis (which only treated the tracking portion after the segment transition point). The linear lateral error for the HUD appears superior to the HDDs, with good localizer captures and very smooth tracking. The most likely causes for the better localizer tracking with the HUD as compared to the HDDs can be attributed to the larger FOV of the HUD at unity minification.

Superior HUD localizer tracking performance becomes even more significant when consideration is given to the order of presentation. Due to the heightened desire to obtain flight test HUD data (since HUD simulation environments are not generally of high fidelity), HUD display concepts were always evaluated first. Thus, any training gained by the pilots during the course of the experiment would favor the HDDs. (Fatigue effects were considered improbable.) It was anticipated that this result would become even more evident if the presentation order of the display concepts were completely balanced to eliminate training effects.

It was also anticipated that reductions of path error would be associated with increases in HDD size. This expectation was based on the decreased MFs associated with larger displays and the manner in which that guidance symbology interacts with the SVS imagery. While the symbology employed for all HDD evaluations was nearly equivalent for all HDDs, one aspect of the flight-path error indication did change appreciably with display size. As observed in the data (and discussed in a following section), pilots selected similar FOVs for all HDDs, creating a situation where specific, but different, MFs were present for each HDD size.

Variations in MF create different amounts of apparent visual flight-path error as indicated by the relationship between the velocity vector and the runway image. Larger MFs (as encountered for the size-A display) make a given amount of path error look smaller to the pilot. Smaller MFs (such as those encountered for the size-X display) make a given amount of path error look much larger. It was anticipated that the larger apparent error, consistent with the larger display sizes and smaller MFs, would enable the pilots to generate less path error for situations in which the runway image was visible on the SVS HDD (for about the last 2 nmi on approach). It was also expected that the trend of reducing flight-path error with decreasing MF would continue until pilot over controlling would become a factor for MFs smaller than those employed by this evaluation. Analyses of MF data are presented in a following section.

Although the statistical analysis of the localizer tracking data after the segment transition point did not show any significant differences among the HDDs (size-A, -D, and -X) tested, the linear lateral error data presented in figure 24 do suggest that pilot performance degraded as display size was reduced for the transition segment, which was the expected trend. The lack of significant differences in results for the RMS lateral tracking error for the HDDs can be attributed to several characteristics of this flight test, aside from the choice to confine tracking analyses to the portion after the segment transition point. For this flight test, only six pilots participated in the study, with a large amount of pilot variability for the transition segment of the approach maneuver. Environmental conditions changed throughout the test, with various crosswinds and turbulence levels encountered, typical of flight test environments. Additional data from more pilots might have generated more significant results since trends are apparent through visual inspection of figures 24 and 26.

For the purpose of evaluation and interpretation of results, one dot of localizer error is equal to 412 ft at the average beginning of the tracking segment (i.e., 2.5 nmi from the runway threshold) and 221 ft at the approximate end of the tracking segment (i.e., 0.5 nmi from the runway threshold) for runway 17C/35C at DFW.

Effect of HDD Display Size or Type on Glide-Slope Tracking

A statistical analysis of the pilot performance data of linear vertical tracking error was performed in a similar manner as linear lateral tracking error (as previously discussed). Mean and standard deviations of RMS linear vertical error are presented in table 7. From table 7 it can be seen that pilots were able to

Table 7. RMS Linear Vertical Error for Tracking Phase

Terrain texturing	Display size or type	Mean, ft	Stdev, ft	Number of samples
Generic	Size-A	25.1	7.8	6
	Size-D	27.7	12.9	6
	Size-X	24.3	20.7	6
	HUD	22.7	10.6	6
	Total	25.0	13.0	24
Photo-realistic	Size-A	33.1	22.0	5
	Size-D	30.5	23.8	6
	Size-X	24.8	14.2	5
	HUD	22.6	17.9	6
	Total	27.6	19.0	22
Total	Size-A	28.7	15.5	11
	Size-D	29.1	18.3	12
	Size-X	24.5	17.2	11
	HUD	22.6	14.0	12
	Total	26.2	16.0	46

control the linear vertical error to within approximately 30 ft RMS for the localizer/glide-slope tracking phase of the runway change maneuver. Unlike linear lateral error, no significant differences exist in the linear vertical tracking data due to display size, type of display, or method of terrain texturing employed.

While no statistically significant results were encountered for linear vertical tracking error after the segment transition point, visual inspection of linear vertical error data, presented in figures 25 and 26, do indicate substantial differences in pilot performance for the different HDDs and HUDs tested. Perhaps as an artifact of the data analysis that separated the runway change maneuver into transition and tracking segments, data for the size-A display generated similar statistical data as the data for the other displays after transition have been completed (i.e., once stabilized onto the target localizer and glide slope). The segment transition points are indicated by the squares with dots on figures 24 through 26.

However, if consideration is given to the entire runway change maneuver, it is clearly apparent that superior control of the aircraft, with a commensurate reduction of linear vertical error, was accomplished for the larger HDDs and HUD, as demonstrated through the linear vertical tracking error data throughout the maneuver. All the reasons previously discussed regarding lateral tracking error for different HDDs and HUD apply to vertical tracking error (i.e., decreased MFs for the larger HDDs and HUDs). However, in addition to the path guidance information provided by the course deviation indicators and the relationship of the velocity vector with the runway image, pilots could also employ the 3° reference line with the velocity vector to manage their flight-path error and vertical trajectory. As was previously discussed regarding the relationship of the velocity vector with the runway image being affected by changes in MF, the relationship of the velocity vector with the 3° reference line was also similarly influenced. Higher levels of MF hampered pilots' use of the velocity vector with the 3° reference line to control flight-path error because a given error in flight-path angle, as indicated by the vertical distance between the center of the velocity vector and the 3° reference line, was reduced for higher MFs.

For the purpose of evaluation and interpretation of results, one dot of glide-slope error is equal to 99 ft at the average beginning of the tracking segment (i.e., 2.5 nmi from the runway threshold) and 50 ft at the approximate end of the tracking segment (i.e., 0.5 nmi from the runway threshold) for runway 17C/35C at DFW.

Effect of HDD Display Size on Selected FOV

One of the primary research objectives of the flight test was to provide data to help establish FOV recommendations for SVS HDDs. To accomplish this objective, pilots were asked to set the display FOV initially to what was desired during the approach, and they were provided with a means to change FOV by using the SVS-RD touch-screen interface. While the touch-screen interface proved to be a somewhat cumbersome control method (alternate methods, such as knobs and buttons on the forward center console, might be preferable), it did provide the ability to change FOV and support the test.

Tables 8 and 9 present selected FOV data for the transition and tracking segments of the approach. The tables provide the mean and standard deviation of the selected FOV as functions of texturing and HDD display size. In addition, the unity horizontal FOV for each display size and mean MF are also provided. ANOVAs of the selected FOV for the transition and tracking phase, with display size and texture method as independent variables, showed no significant main effects or any significant correlations between the two main factors. Therefore, the FOV/display size result is that the selected FOV was independent of display size within the transition and tracking phases. However, pilots consistently selected lower FOVs for the tracking phase than for the transition phase. Pilots selected means of approximately 40° FOV for the transition, and 28° FOV for the tracking portions of the maneuver. The trend of reducing FOVs was observed to continue down to the end of final approach, where many pilots ultimately selected unity FOVs.

Effect of HDD Display Size on MF

Display size, selected FOV, and minification are closely related. ANOVAs performed on the MF for the transition segment and the tracking segment, with display size and texture method as independent variables, showed a highly significant main effect for display size ($F(2,28) = 8.78$; $p \leq .001$, and $F(2,28) = 8.146$; $p \leq .002$, respectively), but no significant main effect for texture method or interaction effects between the two main factors present. Figures 28 and 29 present the results for the display size factor for the transition segment and tracking segment MFs, respectively. Tables 8 and 9 present the mean MFs as a function of texturing and HDD display size for the transition and tracking segments of the approach. In addition, the unity horizontal FOV for each display size is also provided. The inferences from the results concerning display size, selected FOV, and MF are that as the display size increases, the pilots' preference for FOV approaches unity (MF of one). Conversely, these results also indicate that pilots incurred larger MFs for the smaller displays (size-A and size-D) to achieve the desired FOVs while demonstrating the ability to maintain a degraded but similar level of performance.

Therefore, the results of the effect of HDD display size on selected FOV reported in the preceding section can be restated in terms of the MF. The selected FOV/phase-of-flight result mentioned previously can be expressed this way: as range to touchdown decreased, the MF moved toward unity (i.e., no minification). Also, the FOV/display size result can be restated: pilots selected smaller MFs for the larger sized HDDs regardless of phase-of-flight (as display size increased, the MF moved toward unity). If the collimated HUD display is considered to be the largest size display, this restatement applies to its inclusion, as well.

Table 8. Selected FOV Data for Transition Segment

Terrain texturing	Display size	Mean, deg	Stdev, deg	Number of samples	Unity FOV, deg	MF
Generic	Size-A	45.8	11.9	6	12.0	3.8
	Size-D	38.0	15.6	6	14.6	2.6
	Size-X	43.8	26.3	6	22.6	1.9
	Total	42.5	18.1	18		
Photo-realistic	Size-A	41.1	15.7	5	12.0	3.4
	Size-D	33.6	13.8	6	14.6	2.3
	Size-X	36.5	14.5	5	22.6	1.6
	Total	36.8	14.0	16		
Total	Size-A	43.7	13.3	11	12.0	3.6
	Size-D	35.8	14.2	12	14.6	2.5
	Size-X	40.4	21.1	11	22.6	1.8
	Total	39.8	16.3	34		

Table 9. Selected FOV Data for Tracking Segment

Terrain texturing	Display size	Mean, deg	Stdev, deg	Number of samples	Unity FOV, deg	MF
Generic	Size-A	28.0	13.4	6	12.0	2.3
	Size-D	28.8	11.0	6	14.6	2.0
	Size-X	30.6	7.2	6	22.6	1.4
	Total	29.1	10.2	18		
Photo-realistic	Size-A	29.6	7.2	5	12.0	2.5
	Size-D	26.2	7.3	6	14.6	1.8
	Size-X	26.1	3.7	5	22.6	1.2
	Total	27.2	6.2	16		
Total	Size-A	28.7	10.5	11	12.0	2.4
	Size-D	27.5	9.0	12	14.6	1.9
	Size-X	28.6	6.1	11	22.6	1.3
	Total	28.3	8.5	34		

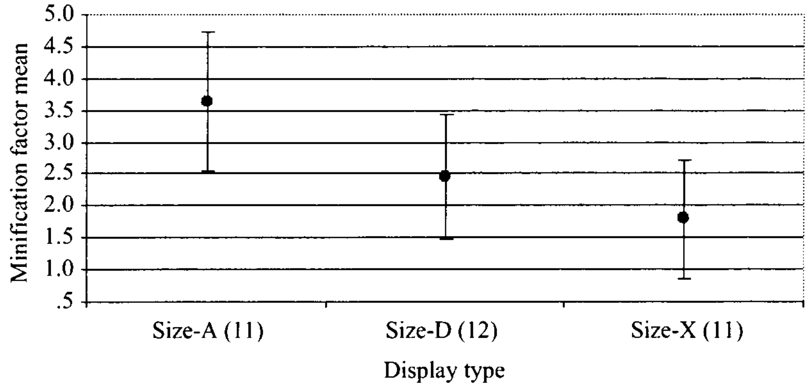


Figure 28. Minification factor for transition phase.

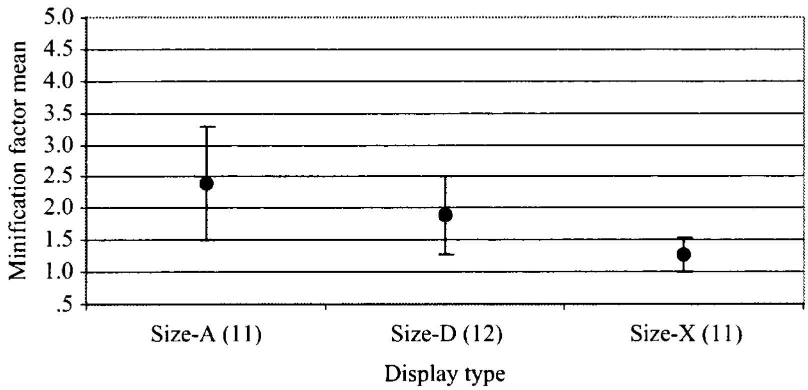


Figure 29. Minification factor for tracking phase.

Inferences From Qualitative and Quantitative Results

One inference from the results concerning display size, selected FOV, and MF is that as the display size increases, the pilots' preference for FOV approaches unity (MF of one). Pilots appear to prefer larger size displays with unity (the HUD) or near unity (size-X display) MFs because the integrated information on these display concepts is easy to interpret and affords better situational awareness. This inference, as well as pilot comments, supports the hypothesis that pilots would like larger physical display sizes because they are easier to use.

Pilots also commented that large MFs produced the illusion that objects portrayed in the SVS display were much farther away than they actually were and that perceived altitudes were much less than actual. Large MFs also created significant runway viewing problems because items subtended much smaller angles on the display than in the real world. However, MFs as large as 4.8 were deemed acceptable for this study.

An inference from the results concerning the terrain-texturing method is that for the limited scenarios tested at DFW, there were no differences in pilot performance between photo-realistic and generic terrain-texturing methods; although, for the most part, pilots preferred the photo-realistic texturing to the generic terrain texturing.

Pilot ratings and comments indicated that enhanced situation awareness was provided by all of the SVS (HDD and HUD) concepts, regardless of display size. These results firmly establish the SVS retrofit concept approach as viable, at least in the benign terrain environment of DFW in nighttime operations.

Conclusions

To introduce synthetic vision systems (SVS) display technology into as many existing aircraft as possible, a retrofit approach was defined. That approach proposed using existing head-down display (HDD) capabilities for glass cockpits (cockpits already equipped with raster-capable HDDs) and head-up display (HUD) capabilities for the other aircraft. That retrofit approach was evaluated and initially validated for typical nighttime airline operations at a major international airport. Overall, 6 evaluation pilots performed 75 research approaches and accumulated 18 hours of flight time evaluating SVS display concepts by using the NASA Langley Research Center's Airborne Research Integrated Experimental System (ARIES) Boeing B-757-200 aircraft at the Dallas/Fort Worth (DFW) International Airport. Results of the study are as follows:

1. While larger display sizes were preferred, effective applications of SVS display technology can be accomplished in aircraft equipped with HDDs as small as size-A (5.25 in. wide by 5 in. tall) with selectable field of view (FOV) techniques.

2. All pilots felt that a single FOV would not be the best solution and would impose undue restrictions on SVS display effectiveness. Pilots recommended multiple FOVs based on phase of flight, such as en route, approach, and others. All pilots indicated that providing only a few specific FOV choices would be better and stressed that the ability to move between the various choices should be made extremely easy, with the selected FOV being obvious. Five of the six pilots recommended an exclusively manual control technique for FOV selection. The pilot with the differing opinion suggested an automatic function with a manual override capability.

3. Pilots selected similar FOVs regardless of display size or terrain-texturing method employed. In addition, pilots consistently selected lower FOVs for the tracking phase than for the transition phase. Pilots selected means of approximately 40° FOV for the transition and 28° for the tracking portion of the maneuver. Stated another way, as range to touchdown decreased, the minification factor (MF) moved toward unity (i.e., no minification). Also, pilots selected smaller MFs for the larger sized HDDs regardless of phase-of-flight. (As display size increased, the MF moved toward unity.)

4. In general, pilot ratings indicated that it was easier to use a head-down primary flight display with photo-realistic terrain texturing than one with generic terrain texturing. All but one pilot preferred the photo-realistic terrain-texturing technique over the generic-texturing technique for both HDD and HUD applications. Four of the six pilots felt it was easier to determine relative position and judge depth perception with the photo-realistic texturing than with the generic texturing for both the HDD and the HUD.

5. Although not specifically queried, half the evaluation pilots volunteered that they preferred the HUD to the HDD. Reasons cited for this preference were that the HUD had a wider FOV, unity minification, enabled the pilot's head to be in a natural position to land (head up, eyes out), and had all the information a pilot needed in one area.

6. Of the five quantitative measures analyzed, three (segment transition point, root mean square (RMS) linear vertical tracking error, and selected FOV) provided no detectable statistical differences between display size (size-A, -D, or -X) or type (HDD or HUD), and terrain-texturing method. In general, pilots were able to re-establish the aircraft onto the target final approach approximately 2.6 nmi from the initial runway threshold at an altitude of approximately 761 ft above ground level (AGL).

7. Pilots were able to achieve statistically significant lower levels of RMS localizer tracking error during the tracking phase for the HUD compared to the HDDs. Differences between the HUD and HDD included, for the HUD, unity minification, the larger FOV at unity minification, collimation, and location, as compared to the HDDs. However, of all these differences, the most likely causes for this result are attributed to unity minification and the larger FOV at unity minification of the HUD.

8. The effect of display size on minification factor (MF) selection for the transition phase and the tracking phase was statistically significant. As the display size increased, the pilots' selected FOV approached unity (MF of one). Conversely, these results also indicate that pilots incurred large MFs for the smaller displays (size-A and size-D) to achieve the desired FOVs while demonstrating the ability to maintain a degraded but similar level of performance.

9. There was no statistically significant effect of display size or type or the method of terrain texturing on the pilot's ability to track the glide slope after the segment transition point. However, graphical inspection of the linear vertical tracking data over the entire runway change maneuver strongly suggests superior pilot performance was achieved for the larger size HDDs and the HUDs tested. Pilot performance variability during the transition segment, combined with a relatively low number of pilots and the choice of metrics, were the primary causes for the lack of statistically significant results.

Based on both qualitative and quantitative results, recommended FOVs for SVS HDDs are (1) 50° for nonfinal approach maneuver segments, (2) 40° for early final approach maneuver segments (i.e., >2 nmi from runway threshold), and (3) 30° for late final approach maneuver segments (<2 nmi from runway threshold).

The top level results of the Dallas/Fort Worth (DFW) flight test concerning the enhanced situation awareness provided by all of the SVS (HDD and HUD) concepts, regardless of display size, are highly significant. These results firmly establish the SVS retrofit concept approach as viable, at least in the benign terrain environment of DFW in nighttime operations. Future assessments need to extend the evaluation of the SVS retrofit approach to operations in a realistic, terrain-challenged operational environment and with testing in daytime conditions. In addition, future SVS testing should include a conventional blue-sky/brown-ground primary flight display (PFD), or similar legacy instrumentation concept, such as a baseline. For this study, it was not possible to establish the overall benefit of SVS displays because no baseline concept was included in the test matrix. Lastly, a more thorough and systematic approach towards understanding the effects of terrain portrayal for HDDs and HUDs should be employed that includes several terrain-texturing techniques combined with variations of digital elevation model (DEM) resolutions to establish the relationship between terrain portrayal fidelity and pilot performance.

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Appendix A

Postrun Pilot Comments

After each run, pilots were asked to respond to the set of questions listed below. If the pilot provided no response, that question was not included in this section of the document. In addition, running commentary by the pilots during the course of the run was also captured and presented in the general section for each run. Questions 6 and 7 were applicable to the HDD evaluations that featured adjustable FOV control. Questions 8 and 9 were applicable to the HUD evaluations that featured a declutter option. Pilot responses are indicated in italics.* The authors of this document added explanations of pilot comments that are indicated in brackets in the text below.

Postrun Questions

Question 1:	Evaluate the ease of flying with this display?
Question 2:	Evaluate the ease of maintaining situational awareness?
Question 3:	Did the scene content (degree of realism) affect your ability to fly using the display?
Question 4:	Did the scene content (degree of realism) affect your ability to maintain orientation or situation awareness using the display?
Question 5:	Performance estimates (once established on final)?
Question 6:	What were your reasons for selecting the FOVs that you used?
Question 7:	If you changed FOVs during the approach, what was your rationale on where to change and why?
Question 8:	Did the real world scene interfere with your ability to use the terrain information in the HUD image?
Question 9:	If you decluttered the HUD during the approach, what was your rationale on where to declutter and why?

Summary of Pilot's Postrun Comments

This section of the report presents a summary of the pilots' postrun comments. Selected pilot comments are included below. Pilot comments that occurred frequently, or that were of particular significance, are included.

1. Pilot 1, photo-realistic HUD: *Once you're in the tunnel it's easy to stay in, but if you overshoot it, it's hard to get back in.*
2. Pilot 1, photo-realistic HUD: *Easier to interpret generic than photo.*
3. Pilot 1, photo-realistic size-A HDD: *I'll take the generic any day.*

* (?) Denotes words lost in transcription.

4. Pilot 1, photo-realistic size-A HDD: *I would get rid of the quick look FOV buttons or make them larger so you don't accidentally push the wrong one. I would give them 10, 30, 45, 60 and let them pick between them. Would recommend a variable FOV for different phases of flight.*
5. Pilot 1, photo-realistic size-D HDD: *I'm changing my opinion on the generic versus the photo. On the bigger picture I like the photo better. It's not anywhere near as fuzzy. I like seeing the runway environment that includes houses, malls, roads, and stuff like that.*
6. Pilot 2, photo-realistic size-D HDD: *I think what I prefer to a higher FOV is the ability to pan to the side the flight director is on. Pan both up and down and left and right, instead of an extended scale.*
7. Pilot 3, photo-realistic HUD: *The photo-realistic enhances your ability to determine your altitude.*
8. Pilot 3, generic size-D HDD: *If I had to pick 2 numbers, I would pick 30 and 60 for the terminal environment and 90 and 120 for en route.*
9. Pilot 3, generic size-A HDD: *I think the terrain display doesn't offer me any depth perception.*
10. Pilot 3, photo-realistic size-A HDD: *The depth perception was better on that one.*
11. Pilot 4, photo-realistic HUD: *With the HUD brighter, definitely better situation awareness capability. The photoreal is definitely photoreal. It's awesome how you can duplicate that so well.*
12. Pilot 5, generic HUD: *Could have done that in instruments once I had confidence that the virtual runway was really overlying the real runway.*
13. Pilot 5, photo-realistic size-D HDD: *Once on final going to unity helps a lot with your perspective on the runway and getting a sense of depth perception and sink rate.*
14. Pilot 5, generic size-X HDD: *One of the things you'll have to get used to with variable field of view is that you are not going to have very good range perception. You're going to have to know exactly what field of view you are in and have a lot of experience with all of the various fields of view.*
15. Pilot 5, photo-realistic size-A HDD: *Overall, I think generic offers you almost as much as the photo-realistic does.*
16. Pilot 6, photo-realistic HUD: *My overall content between photo-realistic and the generic is that the photo-realism made it easier to discern rates of closure with the objects.*
17. Pilot 6, photo-realistic size-X HDD: *It's like flying a day VFR flight. Outstanding.*
18. Pilot 6, photo-realistic size-A HDD: *The photo-realism really helps with crossing angle as well as the rate across the ground.*

Pilot 1, run-7 (photo-HUD with generic-A HDD, nominal):

General:	*Tunnel is disconcerting from HUD viewpoint. Magenta line on head-down is nice to follow. The tunnel can be very disorienting on anything but final. On final it does help. The HUD makes it easy to fly the ILS but then again you're talking to a guy that's flown a lot of HUDs.*
Question 1:	Evaluate the ease of flying with this display? *Somewhat easy.*
Question 2:	Evaluate the ease of maintaining situational awareness? *Somewhat hard in terms of HUD and tunnel.*

Question 3: Did the scene content (degree of realism) affect your ability to fly using the display? *The tunnel helps a lot on final once you intercept glide slope but not on base or downwind. The flight-path marker on the end of the runway on the HUD makes it easier to fly the approach.*

Question 5: Performance estimates (once established on final)? *Max vertical speed about 800. Lateral deviation was one dot to right of course. Max glide-slope deviation was 1 dot above glide slope.*

Pilot 1, run-8 (generic-HUD with generic-A HDD, nominal):

General: *Might be liking tunnel. Once you get in it it's easy to use but getting in it can be a pain. In fact, I'm finding myself using the HUD and the ground map display and ignoring the head-down display. My comment about the HUD is if it could be more than monocolor, it would be great because in the turn, it's hard to pick out what the tunnel, horizon, the heading, and the pitch markers are. Once your wings level it's easy to tell. Changing the range on the touch-screen display needs to be made easier. In turn, hard to tell what are tunnel and pitch markers and horizon markers. Extended centerline track shows real well for the runway. Generic video is better than the photo. It appears to be sharper. Font readability is fine on HUD. The generic video is better than the photo. It's clearer. Reminds pilot it's a computer-generated picture and not a FLIR picture. Can't confuse it with the real world.*

Question 1: Evaluate the ease of flying with this display? *Somewhat easy.*

Question 2: Evaluate the ease of maintaining situational awareness? *Somewhat easy.*

Question 3: Did the scene content (degree of realism) affect your ability to fly using the display? *Did not affect ability to fly.*

Question 4: Did the scene content (degree of realism) affect your ability to maintain orientation or situation awareness using the display? *Like map display. Not using window. Using either HUD or map display.*

Question 5: Performance estimates (once established on final)? *Vertical speed was 900 feet. Max lateral deviation was a (?) at the max; otherwise right on. Max glide-slope deviation was (?) dot high.*

Pilot 1, run-9 (generic-HUD with generic-A HDD, runway change):

General: *The tunnel is lot easier to discern on HUD than head-down display. It might be easier when we go to the size-X display. The ground picture is much better in the generic than in the photo HUD. Flying the tunnel does get easier with practice in the turns but it still does get disorienting. There is one problem with the HUD – with some good crosswinds the HUD FOV may need to be wider. With the F-16 HUD, they had a drift cutout so you could still center the localizer with the flight-path marker. HUD needs to be wider for sidesteps. Wouldn't be able to do this if didn't know where runway was.*

Question 1: Evaluate the ease of flying with this display? *Somewhat easy. Tunnel is getting easier with practice. Even in the turns it's getting a little easier. The nice thing about the tunnel is once you're in it, it's easy to stay in. But once you overshoot it, it's hard to get back.*

Question 2: Evaluate the ease of maintaining situational awareness? *Easy. Did not use head-down display. Used HUD and map display.*

Question 3: Did the scene content (degree of realism) affect your ability to fly using the display? *Generic video is better than photo. Generic is clearer and you don't spend so much time trying to interpolate what is what. Likes map display with groundtrack.*

Question 5: Performance estimates (once established on final)? *Performance estimates hard to evaluate when you do a sidestep. HUD must be wider for two reasons: crosswinds and anytime you're doing a sidestep the two runways are so widely spaced. If you make a good cut to intercept the groundtrack for the approach you could put it off to the side of the HUD.*

Pilot 1, run-10 (photo-HUD with generic-A HDD, runway change):

General: *One comment about the HUD. Regardless of whether it's photo or generic, the settings of the contrast at higher altitudes with less photo requires you almost to have to change the settings as you get closer to the end of the runway because of the brightness [of the raster image] as you approach the ground. For guys who have never used a HUD before, this could be real baffling to them because the HUD is so busy. You have a FLIR picture you're looking at on the ground. You've got all these symbols moving across. I can see where a guy could get spatial disorientation using this. You should talk to Southwest guys to see how they deal with it. Maybe I'm wrong. Maybe it's easy for them. It's only a 20° heading change, and the left runway is off the side of the HUD.*

Question 1: Evaluate the ease of flying with this display? *Somewhat easy.*

Question 2: Evaluate the ease of maintaining situational awareness? *Same brief as earlier. Once you're in the tunnel, it easy to stay in, but if you overshoot it it's hard to get back in. Part of that is subject interpretation, and once they get used to it it'll be easier to interpret.*

Question 3: Did the scene content (degree of realism) affect your ability to fly using the display? *Scene content is good. It's easy to sidestep with that visual. Think generic is better than the photo. Photo tends to be a little blurred. I can see two problems. Once you get closer to the ground, everything will get brighter because all the symbols get closer, and as soon as you break out, the approach lights and runway lights will wash out the HUD.*

Question 5: Performance estimates (once established on final)? *Hard to estimate with sidestep, although the visual approach using the tunnel seemed to be easy to maintain down the center of the tunnel.*

Question 8: Did the real world scene interfere with your ability to use the terrain information in the HUD image? *Easier to interpret generic than photo. Photo is like looking into an IR picture or FLIR picture than generic sim picture.*

Pilot 1, run-17 (size-A with generic-texturing, runway change):

General: *Easier to turn into tunnel without predictive flight-path marker. The last one (predictive flight-path marker), which was Vendor, was harder to use. I guess I'm used to a fixed (not predictive) flight-path marker. Tell the guys that put a flight-path marker on the head-down display—"God bless them." This head-down display is easier to use than the previous head-down display. Easy to interpret with tunnel being magenta and flight-path markers being white. If you're gonna have guys fly the tunnel, then you might have to put a second color in the HUD.*

Question 1: Evaluate the ease of flying with this display? *Somewhere between somewhat easy and very easy.*

Question 2: Evaluate the ease of maintaining situational awareness? *Fairly easy. Not as good as Vendor in terms of map picture but just as good as other picture.*

Question 3: Did the scene content (degree of realism) affect your ability to fly using the display? *Scene content was very good. Doesn't seem to be as accurate as a database because you don't see a database. And it might be good for a pilot to know there's a shopping center and building so he would look for that to look for lights.*

Question 5: Performance estimates (once established on final)? *Max vertical speed is about 1000.*

Question 6: What were your reasons for selecting the FOVs that you used? *Liked wider FOV the farther out I was—like on downwind or base. As I turned final, I wanted a smaller FOV because it gave me more detail out in front, and that's what I'm looking for. I do have one suggestion: if you're going to use this to do sidesteps, then the picture of the 3 runways – the runways should be labeled. That way there's no question which is which. Like if you put a 17C off the end of the runway, then I have no question which it is.*

Pilot 1, run-18 (size-A with photo-texturing, runway change):

General: *Can tell you right now that I like generic better than photo. Same reasons as earlier. Photo appears to be blurred compared to the sharper generic. Different colors on the head-down display makes it easier to interpret where you are in relation to the tunnel. Know you can step up the FOV in 5° options. I don't need all those different options. If you give me 10, 30, 45, and 60, then I know it limits my options but it makes it easier to get from one to another, versus having to step 5 or 6 times to get to what I want. Again, in turn, with different colors it makes it easier to follow the tunnel.*

Question 1: Evaluate the ease of flying with this display? *Somewhat easy to very easy.*

Question 2: Evaluate the ease of maintaining situational awareness? *Easy.*

Question 3: Did the scene content (degree of realism) affect your ability to fly using the display? *Comparing the photo scene to the generic, I'll take the generic any day. The photo keeps looking blurry regardless of FOV and at what distance you are. I do have the comment that if we're going to do the sidestep, I want the runways labeled. The reason is if I'm looking out the window, I can confirm which runway it is, whereas if I'm looking through a small window like this, I can't see all the runways.*

Question 7: If you changed FOVs during the approach, what was your rationale on where to change and why? *I would get rid of the quick look FOV buttons or make them larger so you don't accidentally push the wrong one. I would give them 10, 30, 45, 60 and let them pick between them. Would recommend a variable FOV for different phases of flight. Farther away from the airport you are going to want the wider FOV because you want the big picture, and on short final you want a narrower FOV because you want a more detailed scene. You are not interested in what's to your left or right but what's in front of you.*

<u>*Pilot 1, run-19 (size-D with photo-texturing, runway change):*</u>

General: *This picture looks better than the other. I guess it's because it's a bigger picture and you're able to put more pixels per square inch. Like this one a little better. Looks better than other photo [size-A]. Touch buttons to select FOVs need to be a little bit bigger. Be nice to have TCAS on this picture. To be honest, can't tell a difference in altitude ranges between the two (photo and generic textures). I think the generic looks more realistic to me than the photo.*

Question 1: Evaluate the ease of flying with this display? *The bigger picture gives you a better picture. The bigger display with photo looked better than the little display with photo. Made it easier to fly; have better idea of runway environment. Not as fuzzy as smaller display.*

Question 3: Did the scene content (degree of realism) affect your ability to fly using the display? *No, but it made me feel more comfortable that I knew what the runway environment was going to look like.*

Question 7: If you changed FOVs during the approach, what was your rationale on where to change and why? *Selected wide FOV on downwind and base and then I went to narrow as I got closer. Whenever I'm doing a sidestep, if I have 10° for the nominal and I've been cleared for the sidestep, then I automatically want to go to 30.*

<u>*Pilot 1, run-20 (size-D with generic-texturing, runway change):*</u>

General: *I like this display. The bigger picture on the window to the world and the map display. The side by side gives me better situational awareness than having to look top to bottom on the other displays. In fact, you give me these two displays and the HUD from earlier and I'd be a happy camper. Tape scales ok; although sometimes they do tend to block out stuff. Like in the sidestep it does hide the runway. Still would like to see runways marked 17L, 17R, 17C.*

Question 1: Evaluate the ease of flying with this display? *Somewhat easy.*

Question 2: Evaluate the ease of maintaining situational awareness? *I liked the side-by-side display. I like it better than the display that's in the upper center and the map display that's in the bottom right. It's easier to discern.*

Question 3: Did the scene content (degree of realism) affect your ability to fly using the display? *I'm changing my opinion on the generic versus the photo. On the bigger picture I like the photo better. It's not anywhere near as fuzzy. I like seeing the runway environment that includes houses, malls, roads, and stuff like that. I know that's different than earlier. The smaller photos were so fuzzy you might as well use generic. As the pictures got bigger, I definitely liked the photo better.*

Pilot 1, run-21 (size-X with generic-texturing, runway change):

General: *The bigger the picture, the better the picture. This head down is better than the last, which is better than the one before that. Makes this picture as big as the windscreen and you're gonna have guys screamin' to have this. If you have a strong crosswind, then the flight-path marker is off the side of the head-down display. You may want to consider a locator line when it's displaced off the display so a guy knows which way it's off the display like they do in an F-16 HUD.*

Question 1: Evaluate the ease of flying with this display? *Somewhere between somewhat easy and very easy. The bigger the picture, the better the picture. The compass rose is compressed, and being anal retentive, I don't like that, but I think I can put up with that given the option of the bigger picture.*

Question 3: Did the scene content (degree of realism) affect your ability to fly using the display? *Think I'm gonna like the photo better than the generic because the generic only shows me what's at the airport or just short of the airport. Want it to look like a VFR day. Want to be able to see the golf course and the mall.*

Question 7: If you changed FOVs during the approach, what was your rationale on where to change and why? *Tried unity FOV and can live with that. Options of 20, 30, 45, and 60 and maybe 90.*

Pilot 1, run-22 (size-X with photo-texturing, runway change):

General: [Pilot monitored this approach due to traffic; didn't fly it]. *The bigger view on the head-down display is better. The bigger view on photo is better than the bigger view on generic. I like to see the roads. I like to see the real runway environment. I like to see the VFR day that we all want. The generic is better in the smaller scale when the photo is too fuzzy. But the bigger picture we get, the more the photo looks like real life, so I like that better. I would find it easier flying with photo than the generic. If you just want runway, then generic is fine, but if you want the whole runway environment, then I like it (photo) better.*

Pilot 2, run-7 (photo-HUD with generic-A HDD, nominal):

General: *Autothrottles do make it hard to hold the pitch. HUD and runway overlay (runway outline) looks perfect.*

Question 1: Evaluate the ease of flying with this display? *Neutral*

Question 2: Evaluate the ease of maintaining situational awareness? *Neutral*

Question 3: Did the scene content (degree of realism) affect your ability to fly using the display? *No it did not.*

Question 4: Did the scene content (degree of realism) affect your ability to maintain orientation or situational awareness using the display? *Because it's the first approach, it's a little bit distracting. I was concentrating more on what I was looking at. If I was more familiar to it, it'll be a little more natural.*

Question 5: Performance estimates (once established on final)? *Max vertical speed at 1000 fpm. Lateral deviation (?) dot. Max glide-slope deviation 1/2 dot.*

Question 8: Did the real world scene interfere with your ability to use the terrain information in the HUD image? *No.*

Question 9: If you decluttered the HUD during the approach, what was your rationale on where to declutter and why? *To check correlation between HUD and what I expected to see, and it did. It aligned perfectly with the runway.*

Pilot 2, run-8 (generic-HUD with generic-A HDD, nominal):

General: *Good correlation between HUD and runway.*

Question 1: Evaluate the ease of flying with this display? *Little better than neutral this time due to familiarity.*

Question 2: Evaluate the ease of maintaining situational awareness? *Little better than neutral again due to familiarity.*

Question 3: Did the scene content (degree of realism) affect your ability to fly using the display? *This scene content (generic scene) was more comfortable to fly with than the previous (photo-realistic scene).*

Question 4: Did the scene content (degree of realism) affect your ability to maintain orientation or situational awareness using the display? *No, apparently not. Just as easy as the last one.*

Question 5: Performance estimates (once established on final)? *Max vertical speed about 1100 or 1000, somewhere in there. Lateral deviation less than a (?) dot and glide-slope deviation (?) of a dot.*

Question 8: Did the real world scene interfere with your ability to use the terrain information in the HUD image? *No it did not.*

Question 9: If you decluttered the HUD during the approach, what was your rationale on where to declutter and why? *Same as before—to verify HUD display matched up with the runway itself.*

Pilot 2, run-9 (generic-HUD with generic-A HDD, runway change):

Question 1: Evaluate the ease of flying with this display? *Getting a little bit easier than last time. Halfway between neutral and very easy.*

Question 2: Evaluate the ease of maintaining situational awareness? *The same, improving.*

Question 3: Did the scene content (degree of realism) affect your ability to fly using the display? *No, it did not. Did not interfere or appreciably enhance it.*

Question 4: Did the scene content (degree of realism) affect your ability to maintain orientation or situational awareness using the display? *The degree of realism of the background did not affect it. It was more the runway and symbols that gave you orientation.*

Question 5: Performance estimates (once established on final)? *Max vertical speed about 1000. Lateral deviation once established was about 1/3 dot and glide-slope deviation no more than 1/2 dot.*

Question 8: Did the real world scene interfere with your ability to use the terrain information in the HUD image? *No, it did not.*

Question 9: If you decluttered the HUD during the approach, what was your rationale on where to declutter and why? *Didn't declutter that time; just kept it on the entire time.*

Pilot 2, run-10 (photo-HUD with generic-A HDD, runway change):

Question 1: Evaluate the ease of flying with this display? *Becoming easier; approaching very easy.*

Question 2: Evaluate the ease of maintaining situational awareness? *Becoming much easier.*

Question 3: Did the scene content (degree of realism) affect your ability to fly using the display? *No, not the background. Only the data showing runway and symbols.*

Question 4: Did the scene content (degree of realism) affect your ability to maintain orientation or situational awareness using the display? *No, symbols and data were far more influential there.*

Question 5: Performance estimates (once established on final)? *Max vertical speed about 1000. Lateral deviation 1/2 dot and glide slope rolled out a little too early. Max glide-slope deviation 1/3 of a dot.*

Question 8: Did the real world scene interfere with your ability to use the terrain information in the HUD image? *No, it did not.*

Question 9: If you decluttered the HUD during the approach, what was your rationale on where to declutter and why? *Did not declutter HUD. Comfortable as it was. Did not need to take a peek.*

Pilot 2, run-16 (size-X with generic-texturing, runway change):

Question 1: Evaluate the ease of flying with this display? *Little better than neutral.*

Question 2: Evaluate the ease of maintaining situational awareness? *The same, a little better than neutral.*

Question 3: Did the scene content (degree of realism) affect your ability to fly using the display? *Not necessarily.*

Question 4: Did the scene content (degree of realism) affect your ability to maintain orientation or situational awareness using the display? *No, it did not.*

Question 5: Performance estimates (once established on final)? *Max vertical speed once established on final approximately 1100. Max lateral deviation about 1/2 dot on the localizer. Max glide-slope deviation about 1/2 dot on the glide slope.*

Question 6: What were your reasons for selecting the FOVs that you used? *Used unity for realism. (Actually was on 30° FOV. Pilot thought he was on unity.)*

Pilot 2, run-17 (size-X with photo-texturing, runway change):

General: *Much prefer this display. Realism in this one really enhances situational awareness much more than the other one. Display seems more sensitive, I don't know why (pilot now flying at unity instead of 30° FOV). (Experimenter asked if pilot had any sense of altitude or distance judging cues based on this display.) There was a perception that you could, but I didn't really attempt to make a judgment on distance. I do know when the radar altimeter comes online at about 500 ft that it comes as a surprise. You don't have a sense of being two miles out.*

Question 1: Evaluate the ease of flying with this display? *Much easier than neutral. Approaching very easy in the unity display.*

Question 2: Evaluate the ease of maintaining situational awareness? *That pictorial display was excellent for that...very easy.*

Question 3: Did the scene content (degree of realism) affect your ability to fly using the display? *Yes, this is the first time the extra content, realism of it seemed to give you a sense of assurance of where you're headed. More so than just navigating by runway and ILS.*

Question 4: Did the scene content (degree of realism) affect your ability to maintain orientation or situational awareness using the display? *Yes, it did.*

Question 5: Performance estimates (once established on final)? *Max vertical speed 1000. Lateral deviation was less than 1/2 dot. Max glide-slope deviation probably (?) dot.*

Question 6: What were your reasons for selecting the FOVs that you used? *Wanted to see unity. It was a little more sensitive than 30°.*

Question 7: If you changed FOVs during the approach, what was your rationale on where to change and why? *Changed to unity and left it there.*

Pilot 2, run-18 (size-D with photo-texturing, runway change):

General: *In level flight at unity, can't see horizon. Be nice to have tilt in lieu of that.*

Question 1: Evaluate the ease of flying with this display? *Neutral. Limited FOV; lose flight-path vector in turns off the screen*

Question 2: Evaluate the ease of maintaining situational awareness? *Make it a little less than neutral, and again it's because my flight-path vector is off the screen. It's hard to keep your orientation when that flight-path vector is gone.*

Question 3: Did the scene content (degree of realism) affect your ability to fly using the display? *Yes, it was useful. More so than in the other displays.*

Question 4: Did the scene content (degree of realism) affect your ability to maintain orientation or situational awareness using the display? *Yes. Maybe because I was familiar with the terminal area there.*

Question 5: Performance estimates (once established on final)? *Max vertical speed 1000 ft. Lateral deviation about 1/3 dot and glide slope less than 1/2 dot.*

Question 6: What were your reasons for selecting the FOVs that you used? *Liked unity display but had to higher scale, I think 30, in order to keep flight-path vector on screen in the turns and to have an idea of attitude on that flight-path vector. Not pitch attitude but flight-path vector attitude.*

Question 7: If you changed FOVs during the approach, what was your rationale on where to change and why? *Same as above. My preference at all times would be unity if I could keep it. But in that case, I lost the flight-path vector in the turns. That's why I went to a higher scale. I think what I prefer to a higher FOV is the ability to pan to the side the flight director is on. Pan both up and down and left and right, instead of an extended scale.*

Pilot 2, run-19 (size-D with generic-texturing, runway change):

Question 1: Evaluate the ease of flying with this display? *Neutral to a little easy.*

Question 2: Evaluate the ease of maintaining situational awareness? *Same—neutral to a little easy. Even though this display is a little smaller, I think the familiarity makes it easy.*

Question 3: Did the scene content (degree of realism) affect your ability to fly using the display? *Not as much as photo type.*

Question 4: Did the scene content (degree of realism) affect your ability to maintain orientation or situational awareness using the display? *No, it was more now that the symbols generated for runway localizer, glide slope, heading, sink rate—those.*

Question 6: What were your reasons for selecting the FOVs that you used? *Unity sufficed most of the time. As long as I could keep flight-path vector on there I kept in on unity. And I went up just enough to keep it on.*

Question 7: If you changed FOVs during the approach, what was your rationale on where to change and why? *To keep flight-path vector in view.*

Pilot 2, run-20 (size-A with generic-texturing, runway change):

Question 1: Evaluate the ease of flying with this display? *Particularly easy having full EFIS display all on one screen. Easy display to use, even though view was narrower.*

Question 2: Evaluate the ease of maintaining situational awareness? *Neutral to very easy.*

Question 3: Did the scene content (degree of realism) affect your ability to fly using the display? *Realism wasn't particularly influential.*

Question 4: Did the scene content (degree of realism) affect your ability to maintain orientation or situational awareness using the display? *No, it was more the proximity of all the other standby/generic instruments.*

Pilot 3, run-1 (photo-HUD with generic-A HDD, nominal):

General: *Having trouble following tunnel in the turns. I had to work to find the chicken feet once you lost the tunnel. I had to work a little more than on a clear visual day, but had I been in IMC, it would have been easier. It was harder than a normal visual approach, at least on this run, since I wasn't used to it.*

Question 1: Evaluate the ease of flying with this display? *The ease of flying was a little bit more difficult than a normal visual approach, but easier than an IMC approach. That might have been due to this being the first one. Once straight in again, the terrain enhancement was good.*

Question 2: Evaluate the ease of maintaining situational awareness? *I think the situational awareness, I am going to say, slightly enhanced. I can guarantee later on it is going to get better with training. So much on trying to get used to the HUD visual. I think the more you use it, the better it gets.*

Question 3: Did the scene content (degree of realism) affect your ability to fly using the display? *Anything that helps you gain situational awareness when you can't see the terrain is a viable concept.*

Question 5: Performance estimates (once established on final)? *Maximum vertical speed: During the correction (back to base leg), I was up to about 1,500 fpm. Maximum lateral deviation: At least in terms of full-scale deviation, at least 2 dots out, especially during base leg.*

Pilot 3, run-2 (generic-HUD with generic-A HDD, nominal):

General: *Flying on vertical speed and heading select. Finding it more difficult to maintain tunnel using this mode instead of manual mode but not unreasonable. I find myself working a little more than I would be without the aid of all the neat toys. Almost like micro-management at this point (downwind). So difficult to evaluate the terrain when there aren't any (mountains). I feel much more comfortable this time. Last time I was working so much figuring out what I was looking at. I like the photo-realistic better (than the previous one). I didn't notice any more difficulty flying. In fact it was about the same as the other one. However, the SA for this one was slightly less than the last one since I found the terrain display to be so much better.*

Question 1: Evaluate the ease of flying with this display? *Hard to differentiate between the HUD and the terrain. I think the HUD, of course, helps your situational awareness tremendously. I am just trying to sort out the terrain display and the HUD.*

Question 2: Evaluate the ease of maintaining situational awareness? *Again, it would be a terrific help in a mountainous environment.*

Question 3: Did the scene content (degree of realism) affect your ability to fly using the display? *No, again, there is no terrain out there. I was having to work a little bit more on the HUD, but I was flying more precisely.*

Question 5: Performance estimates (once established on final)? Maximum vertical speed: *Perhaps a 1,000 fpm down, 500 fpm correcting. Kind of hard to deviate from that with the velocity vector. Initially started out slightly left of course, and I knew that, but we overshoot a little bit. Max GS deviation: We started out a little low but corrected for that. That was I think due to the vectors there.*

Pilot 3, run-3 (generic-HUD with generic-A HDD, runway change):

General: *Once you get out of the tunnel, you lose your scan. Tend to focus on the display looking for the tunnel. More time doing that than my normal scan. I think this can be done very easily; well, I shouldn't say that. You have to make a transition from the tunnel to the basic instruments with the glide path there. And I think that is training. I am flying by the glide-slope indicator now. You know, considering all the wind out there, this is actually pretty easy to do. Ok, I didn't think that was too difficult at all, really. I think it was easier on the HUD that it will be head down. If you can train the guys to make the transition from trying to maintain the tunnel, and I know you don't want to hear about the tunnel, but if you can train them to make the transition from that to the glide-path indicator and keep that in your scan, it is a training thing. I didn't find that to be a difficult transition whatsoever. Yeah, I looked at the generic texturing, but without any terrain (mountains), it is kind of hard to elaborate. I can guarantee that if there were some terrain out there, there is no doubt, and if I were in IMC, that my situational awareness would be enhanced. I am trying to focus strictly on the HUD, but there are bright lights out there too.*

Question 1: Evaluate the ease of flying with this display? *I found that, I would say as compared to flying by hand, I am trying to sort out what I should be comparing it to flying with no HDD size-A whatsoever. Somewhere between neutral and very easy. That is because the flight-path vector and all the information supplied to me, makes accommodating the wind and the crosswind easier.*

Question 2: Evaluate the ease of maintaining situational awareness? *The SA is enhanced since the terrain is indicated. I don't find the display cluttered. I find it to be a good display. The first couple of times I tried to occasionally look through the display, sort of a trust issue, I didn't find myself doing that this time.*

Question 3: Did the scene content (degree of realism) affect your ability to fly using the display? *I would say that no, the scene content did not affect my ability to fly the display. Well, yes it did; it did enhance my ability to fly, again with the flight-path vector, and compensating for the wind I didn't have, align the display right there. I sure wish we could throw some terrain in here. I would say that judging the altitude via the HUD is a little more difficult than looking out the window for sure.*

Pilot 3, run-4 (photo-HUD with generic-A HDD, runway change):

General: *Trying to maintain the tunnel distracts me from trying to evaluate the terrain. Hard to do both. I think with the terrain, it is a little bit blurred. If you could enhance that, it sure would go a long way. Looking at all the buildings and seeing through the lights, I am getting a better picture of how the terrain is displayed. Overlaying the terrain depiction is very accurate. I was very concerned for map shifts at first. Roads all seem to be in the right spot. I have a better altitude perspective now that I am concentrating on the terrain. The altitude perspective can be learned. I think the first few times you just have to take that into your field of view, if you will. Making a transition to about a 45° offset, trying to find the runway; okay, there it is. I see the runway. I am flying the vertical path via the glide-slope indicator; I have lost the runway out of my field of view. Trying to find it; there it is. Getting high, there we go. Yeah, if I take more than a 30° cut I lose the runway on the HUD. The roads show up clearly; the taxiways show up clearly. The altitude perspective—I think I am getting better at it. It is feeling good for me anyway.*

Question 1: Evaluate the ease of flying with this display? *That was much easier than the last time I flew the photo-realistic. I think that if you take that into your scan and really concentrate on it, I don't think, now, getting the altitude perspective was as difficult as the generic texturing. The photo-realistic enhances your ability to determine your altitude—your depth perception, if you will. I think that, you know, the display, flying that approach as we did with that display, especially in low-lying clouds or scud, that kind of weather phenomena, I think the display would have made this approach tremendously easier. Of course, without the weather and terrain, it makes it difficult to judge.*

Question 2: Evaluate the ease of maintaining situational awareness? *I liked that. I was really concentrating on altitude and depth perception, much more so than on previous ones, and I felt pretty comfortable with it. I would say SA; I was looking at roads and buildings; SA is much improved.*

Question 3: Did the scene content (degree of realism) affect your ability to fly using the display? *I think the scene content was fantastic. I was overlaying buildings, what not, with actual terrain and lights down there, everything seemed to be in place. The screen was not too cluttered. I am trying to think of some negative things here. As far as flying the display, I think if you can ignore the tunnel, it is that much easier. Initially, I was focusing on the tunnel. As far as the degree of realism affecting my ability to maintain orientation, I think it enhanced it.*

Pilot 3, run-16 (size-D with photo-texturing, runway change):

General: *It would be nice to have a 30° hard button 'cause that seems to be the optimum place to go; 60° seems too large for terminal area maneuvering. It would be nice to have a 30° hard button. Kind of hard to pick up the runway. It is a little fuzzy. This transition here—the runway of course, gets obscured by the altitude tape. I am trying to figure out here which one is the taxiway and which is the runway. Okay, I think I have it figured out. Anymore of a crosswind and that runway would be under the speed tape. It was pretty easy to fly the approach. With a crosswind, the runway may have been uncomfortably close to being obscured by the speed tape. So, uh, I think I took about a 45° cut during the transition. And, until I got within 30° of heading, I had it on 30°; of course when I got within 30° of heading, I found the runway again. I wish it were easier to get to 30, maybe even a toggle switch on the yoke. I think on the transition, it should have been set up on 60, then when I got setup on final, have it go to 30. An automatic toggle would be nice too.*

Question 1: Evaluate the ease of flying with this display? *I think flying the approach is, I am going to have to revert to my old statement that I have to work harder than I would on a visual, but the SA is of course enhanced. The display is pretty good. A little bit fuzzy. Had a little difficulty picking out the runway instead of the taxiway. But, I guess on a somewhat low-visibility day it would have been difficult as well. However, on this clear visibility night, with the runway lights, it was very easy to see the runway. That brings up a good point, on the display, of course, we don't have runway lights. Runway lights sure are a big aide to picking up the runway instead of the taxiway. In terms of the display, it is not as good as real life lights. Perhaps we could find a way of highlighting the runway. Highlighting the active runway would be good.*

Question 2: Evaluate the ease of maintaining situational awareness? *SA, I want to say that my depth perception, at least this time around, was not as good as the photo-realistic on the HUD. Maybe it will take me a couple of trips to get used to it. The size of the display is a good size. I would like to see the borders of the altitude and speed tapes disappear. I think the borders clutter-up the display. I think we got our comment about the crosswind. I have been cycling through the display sizes, and even in the simulator, I have been able to find a use for unity. In the approach environment, 120 is just too far out. I do see a good use for that, though, in en route.*

Pilot 3, run-17 (size-D with generic-texturing, runway change):

General: *I think that instead of having this path, if we had a vertical track indicator like we do on our airplanes today, that would be a lot less distracting and easy to interpret. I had a little difficulty there, until about 5 seconds ago, that I was below the tunnel. Right now, I would like to change my display (FOV), but I have my hands full. Now, if I had a 30, I would go there. But it takes too much work to toggle it. Until I get to within about 20° of the runway heading, the runway is obscured by the altitude tape. There, it is obscured. Depth perception is not real good here. Almost nonexistent really. Okay, I tried to concentrate on getting the right FOVs there. As I mentioned before, it is a little difficult to switch the FOVs there. I would have liked to have 60° in the turn, then make a transition to 30° as we got closer to centerline. As I said, it was difficult to toggle it. Seems to me, my favorite positions are 30 and 60. If I had to pick two numbers, I would pick 30 and 60 for the terminal environment, and 90 and 120 for en route. Depth perception was difficult. I would prefer a visual approach over the lack of depth perception on that. Probably would not get the same answers in terrain and bad visibility. Easy enough to pick up the glide slope. If you expand the FOV, the screen becomes less usable since it becomes so compacted.*

Pilot 3, run-18 (size-A with generic-texturing, runway change):

General: *Actually, 35° or 40° FOV would be nice on the downwind here. As you get close in, you would go back to 30° or 25°. Changing the screen display FOV and lost the tunnel there. Had a large pitch input there, it was my fault. Regarding map scale range, 20 nmi is good for me. Any lower and I would be tempted to use it for lateral control instead of the PFD. This one would sure be nice. I am having to revert to my vertical speed for depth perception. On that heading, about 35°, I have to cut back over to see it, as the localizer is coming around. A 30° FOV is closer to realism in terms of the size of the runway in my window and the size of the runway in the display. I guess to me, it is more unity than (?). I like this display better. I do have to revert, like I said, to my vertical speed indicator for depth perception. I think the terrain display doesn't offer me any depth perception.*

Question 1: Evaluate the ease of flying with this display? *So, in terms of difficulty flying the approach, I would say it was slightly more difficult but less cluttered than the previous display. I like having to revert to vertical speed. I didn't have a problem doing that, just had to take some thinking. Previously, it was intuitive, this time I had to think, Where is my vertical speed? But that is something you get used to. I like this display better since the speed and altitude tapes were not in the way.*

Question 2: Evaluate the ease of maintaining situational awareness? *Situational awareness; I was able to find the runway easier this time. It wasn't obscured by the altitude tape. The lack of depth perception was a hindrance. In order to obtain some depth perception, had to go to the vertical speed.*

<u>*Pilot 3, run-19 (size-A with photo-texturing, runway change):*</u>

General: *Looks like the upper arrows are only coming into view on the tunnel when you get close. You know what would be nice? If when you change FOV, the tunnel would stay the relative size, but the terrain would change. As I get to larger FOVs, the box, tunnel, become harder to fly. Don't see why you couldn't keep the tunnel the same relative size. When you don't have GS information, on downwind and base, it is difficult to know what altitude you should be at if you lose the tunnel, like I just did. Path error on localizer and GS would be nice. Of course you would have to annunciate that so guys would know it is a path. Transitioning to vertical speed at mark. Much better angle here. I can still see the runway up to; just lost it there; it makes sense. I think that was a better display. The depth perception was better on that one. I still have to go to vertical speed to get a comfortable level of depth perception. The screen in uncluttered again. I still like this screen better than the other one. Vertical speed in right there; it is not hard to find. The level of terrain detail is nice. I am not sure I like the daylight scene. I wonder if you had more, less, like a dusk scene. A dusk scene where you could still see the features might be better. Just trying to adjust the brightness of my screen to see if that would make a difference. Anyway, what I am thinking is that this bright blue sky and bright picture, the transition from, the constant focus, the transition to a dark world at night might be difficult. You are used to this daylight picture. It might be tough to make the transition to a night environment. Anyway, I am just bringing up thoughts.*

Question 1: Evaluate the ease of flying with this display? *This display was easier to fly, the depth perception was better, uh, than the generic texturing.*

Question 2: Evaluate the ease of maintaining situational awareness? *Because of the ability to have better depth perception, SA was better than on the other one.*

Question 3: Did the scene content (degree of realism) affect your ability to fly using the display? *I like this screen format better than speed tapes. I mean I love speed tapes, don't get me wrong, but I just think they clutter it up somewhat. Especially on the size that restricts your FOV. I think that the choice of 30 for FOV, since it gives me more of a sense of unity—a good compromise between terrain detail and FOV.*

<u>*Pilot 3, run-20 (size-X with photo-texturing, runway change):*</u>

General: *I don't know if it's the size of the display but the terrain is blurred. You don't want to look at it. My eyes are drawn away from it because of the blurriness. I'm kind of lost right how as to what my vertical deviation is until I get the tunnel back in my field of vision. Would be nice to have DME here. Okay it's out of my FOV here, so I'm cutting my heading off to my intercept angle at 30°. I hold this until I see the localizer come alive. Localizer coming alive, so I start my turn.*

Question 1: Evaluate the ease of flying with this display? *I hate to be inconsistent but if we're gonna have speed tape and borders on there, I would tolerate it more on this larger display than I would on the smaller displays. I feel comfortable with that large display and the tapes there. I think terrain is a little fuzzy. Blurriness is difficult on the eyes and tends to make you not focus on the terrain. With the blurry terrain, I think it detracts from the ability to get a good depth perception. Display size is much better than smaller display sizes. Find it easier to use it. Find it more tolerable with a given field of view. I guess that's because the resolution is better or being that the screen is larger, I can pick things out easier.*

Question 2: Evaluate the ease of maintaining situational awareness? *Would like to have better depth perception with a clearer picture on the terrain.*

Pilot 3, run-21 (size-X with generic-texturing, runway change):

General: *I find trying to follow the tunnel in the right-hand turn that my altitude tape is obscuring the chicken wires.*

Question 1: Evaluate the ease of flying with this display? *I was concentrating on depth perception there and it's virtually nonexistent, especially close in there with the shade of green it was. Having to use vertical speed arrow in order to get depth perception. If we could increase depth perception and the clarity of the terrain display, then I think it would be a very easy display to fly. Liked display a lot, especially the photo-realistic one. I think size of display dictates content of display. I would encourage altitude and speed tape on larger displays but not smaller displays where it uses up too much room.*

Question 7: If you changed FOVs during the approach, what was your rationale on where to change and why? *Smaller the FOV, the more blurry the terrain picture got, so I kept reverting to 30° or 35° as a compromise between the size of the display, the ability to focus on target—1000 foot mark on runway—and the overall clarity of the terrain as compared to the lower field of views.*

Pilot 4, run-7 (photo-HUD with generic-A HDD, nominal):

General: *HUD display is pretty good. Really impressed on the ground back there with the hangar display. The tunnel is easier to see on the HUD than it is head-down. Like it (HUD) with everything. (Pilot was checking out declutter switch.) In the turn, it's quite a bit harder to see the turn indicators and have a tendency to fly on the inside of the turn to keep them in sight. It would be nice to have some sort of leading flight-path vector indication to see how much the curve was. Like in the Vendor display that had a little airplane with an arrow out in front was really helpful. Little bit higher g-turn than I usually like to take with passengers...it's commanding here. Wow, that's quite a view of the runway down there. Really a nice display for night-time. It really helps having that line straight up to the runway. Be nice to have the 3 1/2° glide-path line float with the aircraft symbol. I'm bringing it up to the runway, which will put on in the middle of the tunnel, and then I'll start putting the flight-path vector back to the runway when it gets there. Tunnel is more compelling when you're actually centered in the tunnel. If you get a little bit outside of it, it loses its compelling nature.*

Question 1: Evaluate the ease of flying with this display? *Very close to very easy.*

Question 2: Evaluate the ease of maintaining situational awareness? *Very easy.*

Question 3: Did the scene content (degree of realism) affect your ability to fly using the display? *It made it easy. I guess the most compelling thing on rolling out on final was the nice, long line straight to the runway. And then the terrain display, the peripheral view was just a nice comfort factor that everything was okay.*

Question 4: Did the scene content (degree of realism) affect your ability to maintain orientation or situation awareness using the display? *Yes. I guess the main texture gave you a feeling of the land and passing over it. One thing that would have added to the situational awareness...I couldn't see the other runways. Coming into DFW where you have three runways coming your direction it's always a higher comfort factor seeing those other runways. I'll have to look closer to see if I can see them this time. Some type of outlining the other runways that is not as distinct as the runway you're going to would be helpful.*

Question 5: Performance estimates (once established on final)? *Max vertical speed 800 fpm. Max lateral deviation – wasn't watching it, didn't need it with the display. Essentially on track most of the way down. Same comment on Max glide-slope deviation.*

Pilot 4, run-8 (generic-HUD with generic-A HDD, nominal):

General: *Bank angle cue is a little bit high, which makes it difficult to bring into your scan on the HUD. Head-down textural scene view is quite a bit superior to the all green HUD view. This time coming around it's easier to get the 3 1/2° down line right at the end of the runway before starting down. Yeah, I see the other runways this time around. Were they there last time around? It is very helpful to have the runways there. It's good, useful visual information. The thing I primarily cue on, being an old HUD person, is getting the 3° glide path lined up with the desired touchdown point on the runway and then bringing the flight-path marker to match that line, which usually keeps you on a 3° glide path, as based from the aircraft as opposed to being from the ILS or PAPI/VASI's. The other terrain scene vision is primarily there as a confidence factor that you are in the right place and gives you depth perception as to how quickly you are approaching the runway.*

Question 1: Evaluate the ease of flying with this display? *Where I would have given it an 8.5 the first time around, I would give it a 9 this time, having seen it twice now. It gets a little bit easier each time.*

Question 2: Evaluate the ease of maintaining situational awareness? *Again, probably a 9. I've got 0 to 10 on my scale.*

Question 3: Did the scene content (degree of realism) affect your ability to fly using the display? *Scene content still good. Not as good as the head-down view but adequate probably through the HUD. One thing that's probably easier for me is that I'm familiar with the terrain around here. If I were at a strange airport, I would probably much prefer the head-down view than the HUD view.*

Question 5: Performance estimates (once established on final)? *Max descent rate was 750 fpm. Short final had about a diamond above the glide slope.*

Pilot 4, run-9 (generic-HUD with generic-A HDD, runway change):

General: *River and terrain shadowing are more enhanced than what you would see in the daytime. It's amazing that the HUD view you see in this is very similar to the infrared HUD view you see in the Lantern HUD. It's a lot more comfortable for me to stay on the inside of the cues on the turn. I guess the reason why is that if you get to the outside, you're going to lose the cues, but if you stay on the inside, you feel like you're going to keep everything in view so you can at least make the turn. I'm relying pretty much on HUD right now. The runway's "gonna" come out of view that we're going to here with the HUD field of view. If I had the ability to widen the HUD field of view, I'd do it. I'm trying to estimate where that 3° down glide-path bar is close to the runway, so I have to take a couple of cuts at it to keep that runway in the HUD field of view while I make the transition where I would have normally stayed on that heading and let it go off the side before coming around. I'm holding the flight-path marker slightly above the 3° line until we get on the glide path, and then I'll bring it back to the line.*

Question 1: Evaluate the ease of flying with this display? *Probably a 6. The main reason is that the FOV of the HUD to be able to keep the runway in sight for the angle that I would have liked to make the transition over there. I would've liked to make the cut a little bit sharper so that I could line up and have a little bit longer time on final. As it was, the angle of cut I had, I started to lose the runway off the side of the HUD. Had to take a little bit of a check turn into the runway to maintain it on the HUD even though there was an earlier time that I would've liked to have turned back toward the runway.*

Question 2: Evaluate the ease of maintaining situational awareness? *I would give it a 7.5. Really no problem at all because of the ability to see all the runways clearly outlined on the HUD.*

Question 3: Did the scene content (degree of realism) affect your ability to fly using the display? *I don't know that it had much except for general situational awareness of being able to see how quickly it was going by. It seemed realistic enough for a monochrome-like display.*

Question 5: Performance estimates (once established on final)? *Vertical speed 900 fpm. Lateral deviation not much at all. Glide slope about 1/2 dot low coming in on approach.*

Pilot 4, run-10 (photo-HUD with generic-A HDD, runway change):

General: *Going to turn HUD a little brighter than I did for the first few runs. Oh, it makes a huge difference in the realisticness of the database. I didn't know what I was missing before. It's extremely good when it's turned up. You could even fly a visual pattern using this with knowing visual references around an airfield. It's really nice. One thing that would be nice to add to the HUD symbology would be the waypoints that are head-down on the nav display. If there was some way to depict those on the HUD, it would be really convenient. I'd be real uncomfortable staying in the middle of the tunnel because you lose the right side cues on the right side field of view on the HUD if you turn to keep yourself centered in the tunnel. Tunnel bars at an angle so you can line up the flight-path vector wings with it to maintain the correct bank for the turn. One thing with the display up brighter—makes it harder to see the symbology, which I think, is leading me to be above glide path here, but I'll get back. This is so bright that I can't see anything real world out there, so I hope it's accurate. Just a quick toggle check to verify its accuracy.*

Question 1: Evaluate the ease of flying with this display? *The ease of flying is in the 8.5/9 area. With the HUD brighter, definitely better situational awareness capability. The photoreal is definitely photoreal. It's awesome how you can duplicate that so well.*

Question 2: Evaluate the ease of maintaining situational awareness? *With that display it's about an 8.5.*

Question 3: Did the scene content (degree of realism) affect your ability to fly using the display? *Degree of realism was really good. What I'm going to do this time, with being able to see the scene, is to let the runway go out of the field of view like I normally would. Just watching the scene, because I think there're visual cues out there that I could line up with the runway.*

Question 5: Performance estimates (once established on final)? *Track deviations horizontally were pretty much right on. Glide-path deviations—there were slight ones, maybe a 1/2 dot off. VVI was probably 700.*

<u>*Pilot 4, run-9b (generic-HUD with generic-A HDD, runway change):*</u>

General: [Repeating run since evaluation pilot didn't have brightness turned up the first time he flew this approach.] *I've got the brightness turned way up on this for the generic run. On the tunnel, being used to the steering cue we have on the 737, and that most of the fighter aircraft with HUDs have, where you have a flight director right in the middle of the flight-path marker, gives you something very precise to fly. Where the tunnel is so wide, it makes it more difficult to estimate where the center of the tunnel is, particularly in the vertical view. If I had my "druthers," I'd like to see some sort of steering cue in the HUD itself or close in the tunnel a little bit to make it tighter so that you can get a better relative position of how far off you are. In the tunnel, it's much more comfortable to fly in the inside of the turn. I'm picking it out where the road crosses the river there, and I'm gonna let the runway go out of the field of view and then come back. The only thing about letting the runway go out of the field of view is that you lose your situational awareness of where the 3° line is with relation to the runway. You have some glide-path loss. You have to look at the indicator, which is not as good an indicator as I like.*

Question 1: Evaluate the ease of flying with this display? *The realistic terrain display is a little bit easier than the generic terrain display. I'd give it (generic texture) a 7.5.*

Question 3: Did the scene content (degree of realism) affect your ability to fly using the display? *No change in the scene content as far as affecting the ability. Same as the others. Same with the degree of realism.*

Question 5: Performance estimates (once established on final)? *Max vertical speed right around 700. Lateral deviation on track except for initial final position on 35C which took a little time to get centered up on lateral track. Glide-slope deviation was 1/2 diamond off one time.*

Pilot 4, run-16 (size-A with photo-texturing, runway change):

General: *Certainly a wider field of view on the head-down display now so that it makes it easier to fly down the center of the tunnel because you don't lose the cues on the inside of the turn like you do on the HUD.*

Question 1: Evaluate the ease of flying with this display? *The ease of flying is a little bit more difficult with a smaller display. I would say around the 5 area. Adequate, but not nearly as easy as the earlier displays we looked at.*

Question 3: Did the scene content (degree of realism) affect your ability to fly using the display? *I didn't get as good a feeling of the view of the terrain with the smaller display either. It was harder to read and harder to get the depth feel. Looked realistic enough, but I'd like to play more with the view width. But the method of selecting the view width using the touch screen detracts from your ability to track the course. One of the deviations I had was from playing with that in trying to figure out which way to increase and decrease with the decrement button. I would prefer presets of 30, 60, 90, 120 in a vertical rather than a square pad. And I'd rather have the buttons on the right side so I could change them with my right hand so I could keep flying with my left hand.*

Question 5: Performance estimates (once established on final)? *Max vertical speed 900 fpm rate of descent and lateral deviation were. Not a good clean turn onto the changed runway. Would call it an angling approach. At one time a full 2 dots off on glide-path error. Getting too high, had to dive down during the end.*

Question 6: What were your reasons for selecting the FOVs that you used? *I tried to select the narrower field of view, but everything went out of the field of view of the display, so it required a lot of fumbling to try and find a width where you could keep enough vertical and crosswind displacement of the flight-path vector. That's the main problem. Would be nice to have unity display, but there's not enough vertical coverage to allow that and still keep everything on the display.*

Pilot 4, run-17 (size-A with generic-texturing, runway change):

General: *Looks like the steering cue that's on the nose of the aircraft on the God's eye view display is not there anymore, which shows you your turn predictor. It's a handy thing for these turns. (Software problem during this flight test.) This time I will pay more attention to the deviation diamonds instead of the visual view to make the turns. Although I did expand the view so I could see it better. Probably no difference between generic and photoreal in usability of the displays.*

Question 1: Evaluate the ease of flying with this display? *I think I went to too wide a field of view and missed the runway identification there between runway 35L and 35C. I would say the ease of flying that display in the wider field of view was not as easy as when it's a narrower field of view.*

Question 2: Evaluate the ease of maintaining situational awareness? *I lost situational awareness on the ground there as far as groundtrack being to the wrong runway, although descent rates appeared to be okay.*

Question 5: Performance estimates (once established on final)? *On rollout, I was watching course deviation indicator, and I was thinking it was centered, but I guess it must have slipped a little because I took my concentration off that when I was coming center and went more toward putting the flight-path vector over the runway, and I guessed I picked up the wrong runway.*

Pilot 4, run-18 (size-X with generic-texturing, runway change):

General: *Would be really nice is there were a 30° selection on the field of view. Be really nice to have altitude and airspeed tapes float with the velocity vector. When you get a crosswind situation you're not going to get coverage of the steering tunnel. I like it a lot better with the big display having the nav display immediately to the side of the ADI as opposed to being below and to the right like the other display. I'll take the Vendor anytime over these square corners. Kind of just waiting for that course deviator to turn white before I turn back. Can definitely see the two runways this time. Radar altitude isn't popping up beneath the flight-path vector like I would expect it. (Actually, it appears at 500 ft AGL.) As you would expect, the bigger display is better. Depth was easier to judge, partly due to the texture of the environment and partly because it was easier to see the runway perspective.*

Question 1: Evaluate the ease of flying with this display? *Much easier with a larger display. Much easier to see the runways and make out the terrain and the surrounding texturized synthetic view of the world. All around superior to the smaller display. Even on that bigger display, I would rate the ease of flying, with that tunnel the way it is depicted there, is probably in the 6.5 area. Having the display there is probably 7 or 7.5, having the texture the way it was. It's fairly realistic, especially for night. It's better than black night by a long way.*

Question 5: Performance estimates (once established on final)? *Max vertical speed 700 to 800 ft during final approach phase. Lateral deviation was slight, angling after runway change, but easily controlled and at a reasonable altitude. Glide-slope deviation was probably 1 dot or less, as compared to the previous approach.*

Pilot 4, run-19 (size-X with photo-texturing, runway change):

General: *Would like radar altitude at 2500 ft. I have gauge in my mind where I'm looking for 300 ft at a mile and 600 ft at 2 miles, and so forth.*

Question 1: Evaluate the ease of flying with this display? *There's nothing that you could definitely put your finger on, but it did feel like the real world was more real. As far as depth perception, it might be a subconscious depth perception is better, but consciously it looked about the same. Whole approach felt a little more comfortable, although all parameters might not have been perfect, but there was never a time when my situational awareness was in doubt. I would give it in the 7.5 area as far as the ease of approach, and having the terrain there, I would give it an 8 or 8.5.*

Question 3: Did the scene content (degree of realism) affect your ability to fly using the display? *Seemed pretty realistic. It was a little bit fuzzy. Like coming down short final, the roads had fuzzy edges and the resolution wasn't that great. But it was good enough for feeling out what it really was.*

Question 5: Performance estimates (once established on final)? *Max vertical speed probably 800 ft. Angling approach...at about 900 ft AGL, pretty much on glide-path diamond and lateral steering.*

Pilot 4, run-20 (size-D with photo-texturing, runway change):

General: *I don't see the boxes on the ADI display. Maybe it's because we flew through them. Let me check. Okay, I've got a tallyho on them. We're a little bit above. I'm going to try a little bit wider field of view this time to see if it makes these tunnel corners easier to see or not. Can really see things a lot better this time as far as texture down there. Gives you a lot better terrain awareness on short final.*

Question 1: Evaluate the ease of flying with this display? *Maybe I'm getting used to the display. That one worked just fine, even with the size and everything. Right up there about a 7, 7.5.*

Question 2: Evaluate the ease of maintaining situational awareness? *The display was really nice. I liked having the clear picture of everything coming up on final. It did help with the depth perception, I think, consciously this time.*

Question 5: Performance estimates (once established on final)? *Vertical speeds were about 700 on final. Most tracks were on track. Little bit of an angling final on the 35 Center but completely under control. Rolled out on final for 35 Center at about 1000 ft. Close to centerline by 700. Same comment—would like to see radar altitude come up prior to 500 ft on the flight-path monitor. Liked to also see floating altitude and airspeed scales with the flight-path vector.*

Pilot 4, run-21 (size-D with generic-texturing, runway change):

General: *On that last run, I liked 35° (field of view). Maybe this time I'll try 40 and see how it looks. Runway extension line is a very compelling line. With this display, if there were a centerline like that all the way along the route, it would be nice. I think I actually like this 40° field of view. It makes it a little bit easier to track the lines than the 30 or 25. Unity is just unusable because of the lack of vertical capability. The outside lights get a little distracting in your peripheral view when you come across that road. The more times you see it, the better feel you get for lead points. If you flew with it, I think you could get real used to it. That size-D display is certainly adequate. The 757 size display—you could probably learn to fly with it if you flew it all the time. Could probably learn to adapt to it. Certain amount of training is required, but once you reach that level you could probably do it. However, a general statement, the larger you get, the better it is and the easier it is. There's probably one notch better, like going from 7 to 8 or 8 to 9, with the picture display versus the generic display.*

Question 5: Performance estimates (once established on final)? *700 or 800 fpm on final max descent rate. Pretty much on track all the way down, both vertically and horizontally, with minor corrections.*

Pilot 5, run-7 (photo-HUD with generic-A HDD, nominal):

General: *Can see terrain below. It's helpful, but not real helpful. The HUD is real busy. Easier to do with terrain off. Would still like to have brightness controls for terrain. Separate controls for terrain and symbology. Looks like tiny bit more than 3° is needed to stay in tunnel. I find the speed error to be very useful because I don't have much time to scan the lower display to check my speed. And the speed in the HUD is not real helpful because you really don't know the number that you're supposed to be maintaining. You usually scan relative to a reference bug, and the reference bug changes continually as your gross weight changes. Terrain is pretty useful. I actually like it. (HUD froze during run.) I've reverted to head-down display. Just hit a bird. Watching it to make sure it didn't go down the inlet. Don't see the 3° depression line. Hard to see on head-down display. Need to take advantage of the opportunity to use colors. Flight-path symbol should be different than rest of reference symbology. Got HUD back. The 3° line is much easier to see on the HUD than it is on the A head-down display. I'd like to see glide path and localizer symbol a little easier to read. Localizer symbol gets lost over the parking lot...in areas of high brightness. The real runway is shifted about 1/2 runway width to the left. Like the way the tunnel narrows down but it appears to narrow down, in height but not in width.*

Question 1: Evaluate the ease of flying with this display? *I would give it two tick marks to the right of neutral toward very easy.*

Question 2: Evaluate the ease of maintaining situational awareness? *Would give it one tick mark to the left of neutral because it gave me good situational awareness with regard to outside world, but it took away my situational awareness with regard to the airplane—its configurations and speeds and its status with the checklists and things like that. Overall, when flying the airplane in normal approach mode, I think you are more aware of the system status of the things that are internal to the airplane.*

Question 3: Did the scene content (degree of realism) affect your ability to fly using the display? *The scene content did not help that much. I was really following the symbology. Once we got on final, the scene content, airport background with runways, was very useful in verifying where I was. Up to the point of turning final, the scene content did not help me very much. I think that comment is specific to an airport like this where there is not much terrain.*

Question 4: Did the scene content (degree of realism) affect your ability to maintain orientation or situation awareness using the display? *Helped with my orientation to the outside world but didn't help my situational awareness for status of the airplane.*

Question 5: Performance estimates (once established on final)? *Not sure, probably vertical speed was a max of 1000 ft/min. Lateral and glide-slope deviation were within a dot.*

Question 8: Did the real world scene interfere with your ability to use the terrain information in the HUD image? *Real world did not interfere. Scene on HUD is so compelling with the bright green fluorescent marks that you really aren't aware of what's going on around you. In fact, that bird that hit us, I just saw it the last minute coming out of the corner of my vision, so I didn't even see it coming through the HUD.*

Question 9: If you decluttered the HUD during the approach, what was your rationale on where to declutter and why? *Decluttered because brightness was set in such a manner that it was interfering with my identification of the tunnel before I was aligned with the tunnel.*

Pilot 5, run-8 (generic-HUD with generic-A HDD, nominal):

General: The 3° *depression line pops in and out with localizer and glide-slope needles. Rather you leave 3° line and leave the scales. Just remove the error symbol. That way there's not so much stuff blinking on and off the display. I think there are some training opportunities with this. The more you look at it and develop a set of expectations about what it's going to be like, the easier it is to understand it and the less confusing it is to you. It's too bad the eval pilots only get to see it once. You won't be able to see how they do when they are farther up the learning curve. Would like to see scene referenced to flight-path predictor and not the waterline symbol, so that I get equal view left and right, regardless of the amount of crosswind. As it is, it looks like everything is referenced to waterline symbol of the airplane, which means symbology you are using moves off the side of the display. Would be real useful if virtual runway overlaid the real runway. It's one full runway width off to the left and maybe displaced 1000 ft down the runway. Same thing for left and right runway. Like generic texture better than phototexture on final approach. That's because the airport stuff—the thing that's most important to me—stands out a little better in the generic texture. The runways stand out a little better and the localizer symbol is easy to see. I'm able to see runway extended line, which I didn't see on the phototexture HUD. The 3° line stands out a little better. It might be some combination of the two that you are really looking for. Less cluttered HUD on the final. I like having the localizer and glide-slope raw data. It gives me a warm fuzzy that I'm doing approximately the right thing. When the virtual runway doesn't overlay the real runway, you want to line your velocity vector on the real runway, but that takes you off the localizer. Would like to see boxes narrow down with localizer like they do with glide slope.*

Question 1: Evaluate the ease of flying with this display? *One more tick mark to the right than last display. I think lower clutter level made it easier to fly, especially on final where we're supposed to be doing this evaluation.*

Question 2: Evaluate the ease of maintaining situational awareness? *Same rating as HUD before that reflects an overall rating of situational awareness, which includes my awareness of the airplane, its systems, and checklists. I think the HUD and terrain improves my overall situational awareness with respect to the terrain but not to the status of the airplane and its speeds and things like that.*

Question 3: Did the scene content (degree of realism) affect your ability to fly using the display? *It did help. Particularly on final with seeing the runways and 3° depression line. I think that's most useful of all the information.*

Question 4: Did the scene content (degree of realism) affect your ability to maintain orientation or situational awareness using the display? *Yes, much better feel for bank angle and position over the terrain.*

Question 5: Performance estimates (once established on final)? *Vertical speed maybe a 1000 fpm and lateral and glide slope were probably within a dot.*

Question 8: Did the real world scene interfere with your ability to use the terrain information in the HUD image? *It was less so with this approach than with previous one.*

Question 9: If you decluttered the HUD during the approach, what was your rationale on where to declutter and why? *I did not declutter the HUD. Didn't feel it necessary to do so.*

Pilot 5, run-9 (generic-HUD with generic-A HDD, runway change):

General: *Another interesting observation is that I find it easier to asymptote into the tunnel using the HUD than with the plan view display with its path predictor. This HUD presentation is very, very good not that it can't be improved some. Right now I'm asymptoting into the descending part of the tunnel and it's just as easy as pie. Doing a 3-dimensional task like this using a plan view display with a flight director would be very, very difficult to do. Frankly, I think anyone who's ever played a computer game could jump right in and do this without hesitation. I mean just the part of flying the path. There's a lot of other things you have to do with regard to speeds. I think it's probably an indication of my increasing comfort level with this display that I don't even worry about where I'm raising or lowering the gear and the flaps because the trim changes aren't as difficult for me to deal with as they were when I first started flying this thing. Be interesting to look at the HUD in two other situations. One other situation would be with a terrain-challenged airport. I'd also like to use this in a black hole airport where there is no surface definition at all, where the only sensation you get about your altitude above the ground is what you get from the electronic terrain. Like doing this over water at Langley or something like that. Coming around the corner of the tunnel and having that runway appear magically is just like cake. Little confusing situation because localizer and glide slope are pegged, but yet you have to rely on tunnel. Trying to stay on tunnel and 3° line is not on runway yet. Just a little bit confusing. Now on circling part of maneuver, just trying to keep bank angle enough to keep other runway in sight and using glide slope as my vertical reference. The 3° reference line is not an easy thing to use at this point. Very destabilized maneuver. Lights of airport are blanking out the glide-slope indicator at this point. Fairly short final but localizer is coming in. Not very worried about it because I can see electronic runway. Now the 3° depression line is in the right place. Everything is looking real good. Could land out of this easy.*

Question 1: Evaluate the ease of flying with this display? *No change from previous one. Task was more difficult and pressed limits of display more, but display made it very easy to fly. Could have done that in instruments once I had confidence that the virtual runway was really overlying the real runway.*

Question 2: Evaluate the ease of maintaining situational awareness? *1 tick mark to right of neutral on this more challenging approach. Because of the task of maneuvering from one runway to another, the display improved my overall situational awareness. Didn't change anything with airplane configuration. Task required more situational awareness and HUD display provided that.*

Question 3: Did the scene content (degree of realism) affect your ability to fly using the display? *The scene content was very important, but I don't think the degree of realism was very important. I wasn't using the texture or the terrain. I was really using the runways and the localizer and glide-slope information.*

Question 4: Did the scene content (degree of realism) affect your ability to maintain orientation or situational awareness using the display? *To me the two are equal on this particular task.*

Question 5: Performance estimates (once established on final)? *Saw at least a dot of glide-slope deviation. Lateral was pegged at one point. Probably 1200 fpm at one point.*

Question 8: Did the real world scene interfere with your ability to use the terrain information in the HUD image? *Didn't interfere with my ability to see the real world, but the real world did interfere with my ability to see the HUD glide-slope scale in the maneuver.*

Question 9: If you decluttered the HUD during the approach, what was your rationale on where to declutter and why? *Didn't declutter. Found no need to.*

Pilot 5, run-10 (photo-HUD with generic-A HDD, runway change):

General: *Once again would like 3° depression bar on the display all the time, not blinking on and off with glide slope and localizer. I am aware of a technical concept called cognitive switching. I find myself not looking at both the real world and the HUD presentation at the same time. I might be seeing them both, but I'm not actually looking at them both. I mentally switch back and forth. I momentarily find myself not looking at the tunnel to see a target and then I have to mentally switch back. There's definitely a difference between seeing and looking when it comes to something like this. On base leg, so far no problems. Terrain differences between photo terrain and generic terrain are apparent but not important on this part of the path. I don't feel like I can accurately judge range with this display format. I am aware of the extended runway centerline. I didn't notice it on the last photo run. The terrain does give me a sensation of altitude, but you could probably put me at different gammas and I couldn't tell you differences between several degrees of gamma just using the terrain. In other words, just looking at this, I don't think I could tell you that I was on a 3°, 5°, or 2°. I really need sink rate information (during runway change) in the HUD, particularly if it could be in some sort of graphical form. I've actually lost runway off side of HUD. Can still see (runway) 17R. Just taking it in confidence that 17L is there. The radar altitude numbers are overlaying the head of the runway, and I can hardly read them at all. Need to be moved down further on the display. If I could make two changes to the HUD display, I would add the centerline extended to the runway you are going to, at least if not all the other runways. I would stay generic instead of photo, and I would have separate controls for background terrain and symbology. I would add vertical speed indication, tape type, of some kind.*

Question 1: Evaluate the ease of flying with this display? *Same as before. Generic versus photo texture really doesn't change fundamentally the ease in flying the display. As long as the generic texture includes the runway and the essential information you need to fly relative to the new runway. Would like to see centerline extended to the runway you are going to laid out on the HUD. That would make the transition a lot easier. With a fixed FOV, you could take a bigger cut at the centerline of the other runway and asymptote onto the centerline farther out. We weren't stabilizing until around 400 ft radar, but I was perfectly confident because I saw the runway, localizer, and glideslope errors. It was almost like making a VFR approach.*

Question 2: Evaluate the ease of maintaining situational awareness? *No change.*

Question 3: Did the scene content (degree of realism) affect your ability to fly using the display? *Degree of realism doesn't change very much in terms of the usability of the display for the task being given here. In fact, I think I like generic versus photo-realistic simply because it's not quite as bright and doesn't interfere with the symbology quite as much.*

Question 4: Did the scene content (degree of realism) affect your ability to maintain orientation or situational awareness using the display? *No change.*

Question 5: Performance estimates (once established on final)? *Max vertical speed of 1200–1300 ft. Don't get a situation of sink from HUD.*

Question 9:	If you decluttered the HUD during the approach, what was your rationale on where to declutter and why? *I did not find it necessary to declutter. By setting brightness and contrast, I was able to do what was necessary to get the right combination of what I wanted.*

Pilot 5, run-16 (size-D with generic-texturing, runway change):

General:	*Tunnel is hard to see. Hiding behind horizon line. Can't see if it's descending or level. Kind of looks like it's descending but hard to tell at this point. The speed bug could stand to be a little more apparent. Vertical speed is better than the one on the (?) . It's a little more apparent. Don't like vertical speed scale in same box as altitude. Altitude is a little bit difficult for me to read. Had a momentary sensation that tunnel had started turning. Think what it did was level off and I thought it was turning. Can't fly tunnel in corner at unity. Have a good sensation of altitude with this display. Texture in terrain below gives you a sense of how far away you are. Crow's feet for this display need to be brighter or thicker to give you better definition of the tunnel in the distance. The angular changes in the tunnel are not as apparent as with the other tunnel concept. Lot easier to see turns coming up, particularly vertical changes coming up with their format as compared to this format. I think connecting lines to the crow's feet might be helpful. Going to have to increase sink rate to get to the glide slope. Going to stay with 60° FOV right now. Now, I'm on glide slope and going to use 3° reference line as best I can. Runway has gone behind airspeed tape. Gone to unity (after runway change). Could have landed easily out of that one.*
Question 1:	Evaluate the ease of flying with this display? *I'd give it two tick marks to the right of neutral.*
Question 2:	Evaluate the ease of maintaining situational awareness? *Situational awareness was good. Relatively high workload to do inner loop task, so it takes you out of the cockpit as far as checklists and things like that. Overall, situational awareness is maybe a tick mark to the left of neutral, but situational awareness, relative to terrain, is probably better than it would be under instrument conditions without a display like this.*
Question 3:	Did the scene content (degree of realism) affect your ability to fly using the display? *So far, I don't think so. Realism did give me a sense of altitude that I might not get with a generic display. I'll just have to see.*
Question 5:	Performance estimates (once established on final)? *Max vertical speed at least 1200–1300 fpm. Lateral and glide-slope deviation are not applicable for circling maneuver.*
Question 6:	What were your reasons for selecting the FOVs that you used? *I selected 60 because it gave me good definition of the tunnel and the ability to see the runway while I was maneuvering. Went to unity on final approach, which gave me a better view of the runway. Do like having selectable field of view. I would just like to have a better implementation than the touch screen, and I'd like to have 30 as one of the ones you could select.*

Pilot 5, run-17 (size-D with photo-texturing, runway change):

General: *The path in space without the terrain background is just that, a path in space. You could be going straight up or straight down; you just have no idea. If you got out of tunnel, it would be just a bunch of pink marks. The texture adds 3-dimensional effect that's important. I would suggest having an approach with just symbology. When I get in the corners, my primary reference is the crow's feet in the lower left corner (for lefthand turn). The 90° FOV really gives you more of a 3-dimensional effect. I think I like 90 better for maneuvering part of path. In a full-color display, the photo texture is useful. For instance, I'm going over a big interstate, and if you are familiar with the airport you're going to, that's probably useful information. Kind of verifies you're on the path you're expecting to be on and you're going to the runway you've been assigned to. The right runway is easier to see than the black runway. Would like to see runway I'm going to and runway extended on the plan view display. One thing for sure is that 60 is probably not wide enough and 90 is probably too wide, and there's not enough time to manipulate them. Place I see where 90 is useful is in the climb. It gives you some view of the ground while you are climbing out.*

Question 1: Evaluate the ease of flying with this display? *This one is two tick marks to right of neutral.*

Question 2: Evaluate the ease of maintaining situational awareness? *Could maintain situational awareness but had to be careful changing the fields of view while in a dynamic maneuver. Tried to change to 90° in the circle and everything changed so quickly that I completely lost perspective on where the runway was. Had to change quickly back to 60 to find runway again. Need to know what field of view you want to do the circle at and select it before you begin maneuver. Once on final, going to unity helps a lot with your perspective on the runway and getting a sense of depth perception and sink rate. Unity is the way to go on a short final, but you can't use unity to track the tunnel. Going to have variable field of views for this display format.*

Question 3: Did the scene content (degree of realism) affect your ability to fly using the display? *This display is useful to help pick up visual references. The crispness of the display is not enough to determine where you are, particularly for off-in-the-distance objects.*

Question 5: Performance estimates (once established on final)? *Performance estimates are not real informative on runway change maneuver. Vertical speed was as high as 1400 ft/min but had to be to get back on the glide slope.*

Question 6: What were your reasons for selecting the FOVs that you used? *Because of jitter problems, had to use 6° field of view. Used 60° field of view, have to make asymptoting turn onto the runway. So you can't get stabilized real far out. That's where a centerline extended would be helpful, so you could fly over to the line and make a sharper turn and get stabilized sooner.*

Pilot 5, run-18 (size-X with photo-texturing, runway change):

General: *The altitude tape could stand improving. It's kind of busy and jittery. Like altitude tape from better. Easier to interpret at a glance. Like the X display better. Have more of a 3-D effect with it. See more terrain at the bottom of the display. Have sensation of altitude more with this display. However, I don't think performance is improving any with it. I've been trying to change fields of view, but touch screen is being real uncooperative. Cut the corner same as I did with size-D display. Speed error on left wing is real helpful; 90° field of view just loses so much detail of terrain in background—so much detail in terrain that it's not real evident where runways are sometimes. Have to increase sink rate to catch glide slope. Something HUD is missing that is real useful is having that sink rate indication. The X display is really helping me get a sharper angle on the runway here. Circling maneuver is easier with the X display at 60° than D size display at 60°.*

Question 1: Evaluate the ease of flying with this display? *Another tick mark to the right compared to the size D; three tick marks to the right on the X.*

Question 2: Evaluate the ease of maintaining situational awareness? *Bigger the display size, the more value a phototerrain had because you can see more detail in it. Whether it's necessary or not, I don't know. I think some sort of terrain background is important in giving you a proper perspective of the path you are flying.*

Question 3: Did the scene content (degree of realism) affect your ability to fly using the display? *I don't think the scene content affected my ability to fly the display. In fact, the photo-realism on final approach was almost a little distracting, like the white concrete things going here and there. I could see circumstances where you could get confused on what's a major artery running parallel to the airport and a runway.*

Question 5: Performance estimates (once established on final)? *Vertical speed about 1400 fpm.*

Question 6: What were your reasons for selecting the FOVs that you used? *Discussed comments on FOV while I was using them.*

Pilot 5, run-19 (size-X with generic-texturing, runway change):

General: *Generic terrain is perfectly adequate for giving you 3-D sensation of height above terrain. I think the 120° field of view is a bit much. Takes away your ability to track the tunnel. Spreads everything out; 90° is favorite with the X display; 60° was favorite for D display; 90 is adequate for tracking the tunnel, at least the straight part of the tunnel. I like having some type of commanded information, whether it's a 3-D perspective box, or flight director needles, or V-bars. Just flying relative to tunnel perspective really pulls your attention away from other things. With generic terrain would get pretty boring because terrain would always look the same with the exception for the grosser features like mountains and so forth. This scale factor (90°) really puts runway off a long way in the distance. One of the things you'll have to get used to with variable field of view is that you are not going to have very good range perception. You're going to have to know exactly what field of view you are in and have a lot of experience with all the various fields of view. Probably only want two or three max fields of view available. Do not have sensation of altitude with this display like I did with the other one. On the other hand, this one is less cluttered. The 3° depression line and the glide slope don't agree all the time. Could have landed out of that one easy.*

Question 1: Evaluate the ease of flying with this display? *Two tick marks to the right of neutral, based entirely on the circling maneuver. Flying the downwind, base and turn to final was probably a hair easier with generic than it was with photo-realistic. The circling maneuver itself, once I rolled out to final on 17 left, I actually preferred generic because it was easier to see the runway. But when I started circling maneuver, the photo terrain gave me more of a sense of height and depth perception than generic terrain did. One type of format seems to be better in one part of the maneuver and other format seems to be better in another part of the maneuver. Overall, I think photoreal offers so little over generic that if it costs a lot more or is more difficult, I don't see where it would pay for itself right off the bat. Once again, this is at a nonterrain-challenged airport.*

Question 2: Evaluate the ease of maintaining situational awareness? *Situational awareness was good throughout. The 90° field of view I don't think helped me over 60°. It blurred everything. That might be why I didn't have a sense of depth perception. I would give it 1 tick mark right of neutral.*

Question 3: Did the scene content (degree of realism) affect your ability to fly using the display? *Didn't make a lot of difference except that in actual circle to runway, it seemed to make a little difference.*

Question 5: Performance estimates (once established on final)? *Vertical speed was about 1400 fpm. Other two N/A for circle maneuver.*

Question 6: What were your reasons for selecting the FOVs that you used? *Already discussed field of views chosen.*

Pilot 5, run-20 (size-A with generic-texturing, runway change):

General: *In this display, all the scales are compressed toward center of display, but there's a lot more room to spread them out to the sides of the display. Should get some of the numbers out of the center of the display. Move the scales left and right out of the center of the display. Don't work as hard with these displays as compared to the format, but you're not anywhere near as accurate. You're just sort of somewhere in the tunnel most of the time. The magenta line that shows your path in the plan view display looks like it's not as thick as it was in the other displays. Lot easier for me to check speed with the analog display with the orange bug on it. Sink rate is about the same. Altimeter is easier to read. Tapes could use some human factoring. Should look at Airbus 777 and formats and take the best of all three. Circling with 60° field of view this time. Could have landed out of that one.*

Question 1: Evaluate the ease of flying with this display? *That was tick mark to the left. The A, D, and X displays are separated by a tick mark for each of them for ease of flying, mainly because of reduced field of view. I think the 120° was unusable. I like 90 for the climb; 60° for the downwind, base, and turn to final; 60 for runway change maneuver and unity is the way to go once you get on final.*

Question 2: Evaluate the ease of maintaining situational awareness? *Tick mark to the left, probably neutral. Definitely lose something in the smaller displays.*

Question 3: Did the scene content (degree of realism) affect your ability to fly using the display? *I don't think the degree of realism on the terrain made a difference. Each format has some advantages. Have more height and depth perception from photo-realism, but main features of the airport, like the runways, are easier to pick out with the generic.*

Question 5: Performance estimates (once established on final)? *Max vertical speed was about 1400 fpm or somewhere in that range.*

Question 6: What were your reasons for selecting the FOVs that you used? *Field of view has already been discussed.*

<u>Pilot 5, run-21 (size-A with photo-texturing, runway change):</u>

General: *You ought to give size-D or X display on last run so that you leave safety pilots set up for a landing. Picking out the runway out of the clutter is not an easy thing to do. This display is really looking goofy with unity. You can't use unity. With unity, the runway and symbol went right off the bottom.*

Question 1: Evaluate the ease of flying with this display? *The same as the last display. Generic versus photo doesn't make any difference there.*

Question 2: Evaluate the ease of maintaining situational awareness? *Same. Photo versus generic doesn't make much difference with regard to situational awareness. Primary outside situational awareness is relative to airport and runway, and both displays give you that information. Generic is less cluttered. Overall, if I could only choose one, I think I'd choose generic. That would be true for all head-down sized displays. I don't think photo-real displays offered very much, especially in the smaller sized displays like the A. The difference between photo and generic in D-size displays is a little more apparent but not real important. In the X-size display, where you start to pick up some of the terrain detail, I can see where photo-realistic has some value. There you might be able to say "okay, there are the docks or there is the mouth of the river," which would give you some verification that you were in the right place. At the smaller sizes, it's too blurred to really tell that much about it. Overall, I think generic offers you almost as much as the photo-realistic does. Once again, everything is according to the size of the display.*

<u>Pilot 6, run-7 (photo-HUD with generic-A HDD, nominal):</u>

General: *Database looks pretty cool. You can see the buildings down there, at least the patterns of them. Seems to match up really well. Runway centerline looks pretty slick. I just realized I've been flying with the HUD and not through the HUD in the distance. There's plenty of cueing coming off the HUD. This is amazing. An amazing system. The image in the HUD doesn't quite line up with the runway but it's pretty darn close. It's pretty easy to fly.*

Question 1: Evaluate the ease of flying with this display? *I say it's about a 7 out of a 10.*

Question 2: Evaluate the ease of maintaining situational awareness? *8 out of 10.*

Question 3: Did the scene content (degree of realism) affect your ability to fly using the display? *The realism was really quite good. I found myself looking at the display more so than looking through it at the real ground and runway.*

Question 4: Did the scene content (degree of realism) affect your ability to maintain orientation or situational awareness using the display? *I felt that the ground environment really did help with the situational awareness. The only comment is that it didn't quite line up when we were out about a mile and 1/2 from the runway. About (?) runway width displaced to the left from the real one. Other than that, quite easy to fly with.*

Question 5:	Performance estimates (once established on final)? *Wasn't looking at those max vertical speed, lateral deviation, and glide-slope deviation. At one point, appeared to be all on.*
Question 8:	Did the real world scene interfere with your ability to use the terrain information in the HUD image? *When I got within 500 ft, I wanted to turn image on HUD down so that I could have a better cueing of the runway because it became more important for me to see that than what was happening in the HUD. It was important to dim the image on the HUD.*
Question 9:	If you decluttered the HUD during the approach, what was your rationale on where to declutter and why? *I didn't do the declutter. I'll try to do it this time.*

<u>*Pilot 6, run-8 (generic-HUD with generic-A HDD, nominal):*</u>

General:	*I'm used to looking at the flight mode enunciators, speed commands. It would be nice when you guys get that on here. Looks like the horizon on the HUD is 3° above the actual horizon. Terrain looks correct. The longitudinal displacement looks fine. It's still about 1/2 runway width to the left from the real one. Rates of descent are normal for this type of approach: 700 ft, 600 ft. The runways match up now (around 1200 ft AGL). This is rock solid when you have the flight-path vector there. (Principal Investigator asked if pilot had a preference over photo or generic texturing.) I liked the photo part of it. It seemed more realistic, crisper lines.*
Question 1:	Evaluate the ease of flying with this display? *Let's give it an 8 out of 10.*
Question 2:	Evaluate the ease of maintaining situational awareness? *8 out of 10.*
Question 3:	Did the scene content (degree of realism) affect your ability to fly using the display? *The degree of content was just fine, except when I got to about 500 I just decluttered it one level. On the next approach, I'll leave the declutter on for the final portion of it. There just seems to be a lot of information as well as trying to advocate the aircraft to a landing.*
Question 4:	Did the scene content (degree of realism) affect your ability to maintain orientation or situational awareness using the display? *The scene content works just fine for telling you where you are, and it's extremely easy to fly.*
Question 5:	Performance estimates (once established on final)? *Max vertical speed was anywhere between 600 to 700 ft. After I centered up on localizer, it didn't seem to deviate more than 1/2 dot. Glide-slope deviation seemed rock solid on. There's always a little work to keep flight path on the runway*
Question 8:	Did the real world scene interfere with your ability to use the terrain information in the HUD image? *No, I didn't see that happen.*

<u>*Pilot 6, run-9 (generic-HUD with generic-A HDD, runway change):*</u>

General:	*The angle that I'm cutting is causing the runway not to be quite in the HUD. There's the center runway. Looks like there's a road that runs across this sharp zigzag. I think I was noticing the buildings that were coming into view as you get closer. Makes it look like a sharper image.*
Question 1:	Evaluate the ease of flying with this display? *I felt it was so easy. I felt like I could do this all night. It was great, man. I would move it to a 9.*
Question 2:	Evaluate the ease of maintaining situational awareness? *About 8.5 on that one.*

Question 3: Did the scene content (degree of realism) affect your ability to fly using the display? *I felt that there is no real problem in using that level of content to shoot the approach.*

Question 4: Did the scene content (degree of realism) affect your ability to maintain orientation or situational awareness using the display? *No, I don't think so; it affected my ability to maintain situational awareness.*

Question 5: Performance estimates (once established on final)? *I felt that the vertical speed and lateral deviation were stabilized most of the time, well within safe parameters for a landing.*

Question 8: Did the real world scene interfere with your ability to use the terrain information in the HUD image? *Not at all. It seemed to match up pretty well.*

Question 9: If you decluttered the HUD during the approach, what was your rationale on where to declutter and why? *Didn't use declutter.*

Pilot 6, run-10 (photo-HUD with generic-A HDD, runway change):

General: *This is a lot of fun you guys. I'm going to leave the runway in the field of view of the HUD. Here comes the glide path.*

Question 1: Evaluate the ease of flying with this display? *Make that a 9.*

Question 2: Evaluate the ease of maintaining situational awareness? *Actually, let's make both of them 8.5.*

Question 3: Did the scene content (degree of realism) affect your ability to fly using the display? *My overall content between photo-realistic and the generic is that the photo-realism made it easier to discern rates of closure with the objects.*

Question 4: Did the scene content (degree of realism) affect your ability to maintain orientation or situational awareness using the display? *Once again, I flew as much as possible on the synthetic vision display. As I was flying the display, I referenced the outside world just beyond it. When you're doing it in that fashion it makes it really easy.*

Question 5: Performance estimates (once established on final)? *Max vertical speed was probably 1400 ft. Max lateral deviation didn't really apply until on final, and it didn't really move that much. Glide-slope deviation basically caused because runways displaced from each other beyond the glide slope for one.*

Question 8: Did the real world scene interfere with your ability to use the terrain information in the HUD image? *No.*

Question 9: If you decluttered the HUD during the approach, what was your rationale on where to declutter and why? *Did not use declutter. Wanted to see what it looked like doing runway change maneuver in the HUD. Wanted to see how easy it was to do. Was thinking about how other pilots working for the same airline would be able to do that. To me, it looks an awful lot like the simulator, but with the tactile feel you get with the airplane using a synthetic view. The airplane is much more honest than the simulator. So, the ability to fly using the HUD was easier to do than in the simulator because of the feel. In simulator, you have the problem of not matching quite like the airplane feels. In a way, it's the best of combining both worlds.*

<u>*Pilot 6, run-17 (size-X with photo-texturing, runway change):*</u>

General: *It's like daytime here.*

Question 1: Evaluate the ease of flying with this display? *I give it a 9.*

Question 2: Evaluate the ease of maintaining situational awareness? *I give it a 9.*

Question 3: Did the scene content (degree of realism) affect your ability to fly using the display? *Yes. It's like flying a day VFR flight. Outstanding.*

Question 4: Did the scene content (degree of realism) affect your ability to maintain orientation or situational awareness using the display? *Changing the scales. I'm not sure what scale is best for making the cut over and lining up on final for the second runway. Let me fly a couple more and get used to it.*

Question 5: Performance estimates (once established on final)? *Max vertical speed was probably around 1200. Lateral deviation—I'm not sure if I got on the centerline of the second runway. I made an initial cut and then took my cut out and crabbed over most of the time. Max glide-slope deviation about 1/2 dot to 3/4 dot low.*

Question 6: What were your reasons for selecting the FOVs that you used? *The 30, 35 maybe 40° for flying the tunnel gave you good perspective for that, but then I had to increase the field of view to make the cut across. Then I narrowed it down a little too much when I tried to intercept final. Occasionally, I took a peek outside. In this case, 1 peek is worth a 1000 scans. The peek just confirmed where I was. It helped me verify that's what I wanted to do.*

Question 7: If you changed FOVs during the approach, what was your rationale on where to change and why? *I already answered this question.*

<u>*Pilot 6, run-18 (size-X with generic-texturing, runway change):*</u>

General: *Selected unity on this approach at this point (on final before runway change) because it really seems to make it easier to fly the tunnel. The terrain is looking pretty good. Doesn't seem to be too much difficulty flying against it. The runways don't stand out as much as they did in the yellow and black on the Vendor display. Unity really makes it nice once you roll wings level.*

Question 1: Evaluate the ease of flying with this display? *Still give it a 9.*

Question 2: Evaluate the ease of maintaining situational awareness? *Give it a 9 as well.*

Question 3: Did the scene content (degree of realism) affect your ability to fly using the display? *Yes it did. The thing you get with more photo-realism is, the rate at which you move across the ground, the closure with objects, that's commensurate with your speed. It's a little easier to see. In this case, didn't see it as much. I'm not sure if there were any rectangular objects in the photo-realism or not. The rectangular shaped buildings around Dallas are aligned with the roads and with the runway, which gives you an easier time lining up on final. Makes it easier to line up with final when you have something along the centerline of the runway. With the generic background, it tends to be all opaque as far as cueing goes, as far as lining up on final with the runway.*

Question 5: Performance estimates (once established on final)? *Max vertical speed might have reached 1500. Lateral deviation, once we lined up, looked pretty good. Seemed to me glide slope might have been a little low.*

Question 6: What were your reasons for selecting the FOVs that you used? *Reasons were as stated before. When I went to unity, I made a comment that it was easier to fly the pitch modes and roll on the short final segment below 700 ft. Wider fields of view were great for crossing over to the other runway, keeping that runway in view, even though it went behind the speed tapes. Flying 30–45° fields of view for flying the tunnel.*

Pilot 6, run-19 (size-A with generic-texturing, runway change):

General: *Touch screen doesn't seem to be working. (Computer operator adjusted field of view for evaluation pilot.) Let's try 35° field of view. That's a great 3D effect. How about 35° on the field of view. (Computer operator having trouble adjusting field of view, not responding properly.) That's okay, I can still fly like this. It's just that the wider field of views make it easier to fly around the tunnel. This is going to work just fine. How about unity on the field of view. How about 30° of the field of view. That's better. You can see more terrain and see the other runways a little bit better. Okay, going to need 60° field of view, 55°, somewhere in there. That zigzag line looks like a road or a river. Could I get back to 30° field of view. (Principal investigator asked the evaluation pilot if size-A was usable for a synthetic scene.) Oh yeah, I think so. What I think is to simply change field of view. May need to select more different fields of view. Maybe more than 1 or 2. May need a third one in there to help with that.*

Question 1: Evaluate the ease of flying with this display? *Although it was smaller, it seems like a slight change in the fields of view might make up for a lot of the difference. There's not as much cueing from this because there is not as much peripheral stuff that you pick up in the smaller fields of view as far as the terrain goes. I still give it an 8.5 for items 1 and 2.*

Question 3: Did the scene content (degree of realism) affect your ability to fly using the display? *I felt that there was no problem flying this display at all. There was plenty of content for both 3 and 4. With number 4, I had good situational awareness.*

Question 5: Performance estimates (once established on final)? *1/2 dot low from time to time on final.*

Question 6: What were your reasons for selecting the FOVs that you used? *Reasons for selecting the field of view were the same as before.*

Pilot 6, run-20 (size-A with photo-texturing, runway change):

General: *You can see the north/south lines down there. It helps you line up with where it is you want to go. Occasionally, I do notice myself following the crow's feet—spending time at that rather than flying the jet. Watching the crow's feet go by. The photo-realism gives you a better idea for rate of change across the ground. Unity seems to be a little bit too small a scale for making good corrections. Maybe it's because I needed to see something down lower. The photo-realism right here gives you cueing for your crossing rate, your track across the ground, lining up your angles with the extended centerline. The rectangular buildings tend to help you choose a better lineup, which I think resulted in the better roll onto final. Now, if I could just keep it there.*

Question 1: Evaluate the ease of flying with this display? *For questions 1 and 2, I give them both a 9.*

Question 2: Evaluate the ease of maintaining situational awareness?

Question 3: Did the scene content (degree of realism) affect your ability to fly using the display? *The photo-realism really helps with crossing angle as well as the rate across the ground. It helps determine when to roll back toward the runway for the final approach segment, which I think allowed me to do better for item 5.*

Question 6: What were your reasons for selecting the FOVs that you used? *Same reasons as before. Although on that last segment, I was trying to select unity, and it went to 90. That really took more of my time away from flying the jet. Other display is usable, especially with the photo-realism.*

Pilot 6, run-21 (size-D with photo-texturing, runway change):

General: *You got these buildings on the extended centerline so you can just fly over to them and then make the left turn onto final. The photo-realism really helps. You don't get that on the other display.*

Question 1: Evaluate the ease of flying with this display? *I'd give this a 9 as well, maybe a 9.5 on items 1 and 2.*

Question 2: Evaluate the ease of maintaining situational awareness?

Question 3: Did the scene content (degree of realism) affect your ability to fly using the display? *When you've got the buildings out there, you can use them to help you fly the approach. You start navigating off the database. That helps with item 5 for the performance.*

Question 6: What were your reasons for selecting the FOVs that you used? *The fields of view were set for different phases of flight. Flying the tunnels at about 30 or 35. Making a transition to the other runway at 60, 55 might be better. For final approach, I switched to unity; although I think 30 or 25 might be better. Just a smaller field of view for trying to make those finer adjustments.*

Pilot 6, run-22 (size-D with generic-texturing, runway change):

General: *The field of view is stuck again at 30; 30 works fine for doing this. How about 40° or 45° field of view? That's good. Brings in a few more of the turning cues. Seems like speed and altitude tapes obscure some of the turn cues, so going to a wider angle field of view allows for easier navigation down the centerline. This crosswind of 26 to 25 knots forces the cues to the right-hand side a bit. How about 25° field of view. Okay, back to 30 please. That's good, thanks. Can I get unity on the screen? Thank you.*

Question 1: Evaluate the ease of flying with this display? *Let's give a 9 on 1 and 2.*

Question 2: Evaluate the ease of maintaining situational awareness?

Question 3: Did the scene content (degree of realism) affect your ability to fly using the display? *The scene content didn't have as much. Although having flown it a couple of times with this degraded or not as crystal clear as the photo quality, you end up guessing where the runway centerline is. Give credit to the fact that you can teach someone like me how to fly one of these things.*

Question 5: Performance estimates (once established on final)? *About the same as before.*

Question 6: What were your reasons for selecting the FOVs that you used? *The fields of view? I can't make any new comments on that.*

Appendix B

Postflight Questionnaire

Subject ID:__________________ Flight ID:________________

Date:________________ Experimenter:____________

Synthetic Vision Display Evaluation

Size-A Display Evaluations

Based on the *Size-A primary flight display* that was presented to you during the flight evaluations.

1. Please evaluate the ease of performing a landing approach.

|____|____|____|____|____|____|____|____|____|____|

Very hard	Somewhat hard	Neutral	Somewhat easy	Very easy

2. Please evaluate the ease of interpreting airspeed information.

|____|____|____|____|____|____|____|____|____|____|

Very hard	Somewhat hard	Neutral	Somewhat easy	Very easy

3. Please evaluate the ease of interpreting altitude information.

|____|____|____|____|____|____|____|____|____|____|

Very hard	Somewhat hard	Neutral	Somewhat easy	Very easy

4. Please evaluate the ease of interpreting flight-path vector.

|____|____|____|____|____|____|____|____|____|____|

Very hard	Somewhat hard	Neutral	Somewhat easy	Very easy

5. Please evaluate the ease of interpreting vertical speed information.

|____|____|____|____|____|____|____|____|____|____|

Very hard	Somewhat hard	Neutral	Somewhat easy	Very easy

6. Please evaluate the ease of interpreting ILS/precision approach deviation indicators.

|____|____|____|____|____|____|____|____|____|____|

Very hard	Somewhat hard	Neutral	Somewhat easy	Very easy

7. Please evaluate the ease of predicting flight path.

|____|____|____|____|____|____|____|____|____|____|

Very hard	Somewhat hard	Neutral	Somewhat easy	Very easy

8. Please evaluate this display for ease of maintaining spatial awareness while flying the approach.

|____|____|____|____|____|____|____|____|____|____|

Very hard	Somewhat hard	Neutral	Somewhat easy	Very easy

Comments (Questions 1–8):____

____

____

9. Please evaluate the ease of maintaining situational awareness. Note: One could define situation awareness as *"...the pilot has an integrated understanding of the factors that will contribute to the safe flying of the aircraft under normal or non-normal conditions."*

|____|____|____|____|____|____|____|____|____|____|

Very hard	Somewhat hard	Neutral	Somewhat easy	Very easy

Comments____

____

____

10. Please indicate the FOV that you thought most preferable (and selected during experimental test runs) for the Dallas/Fort Worth database.

Comments____

____

____

11. Please evaluate how the FOV you selected (indicated "pilot choice" below) affected how confident you were in your knowledge of your **separation from terrain**.

Pilot |____|

choice Low High

12. Please evaluate how the FOV you selected (indicated "pilot choice" below) affected how confident you were in your knowledge of your aircraft's **flight parameters and flight vector**.

Pilot |____|

choice Low High

13. Please provide any comments regarding whether the FOV requirements would change as a function of phase of flight. Example: "I would like to use 90 FOV for cruise but unity FOV for approach."

____

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____

14. Based on your comments in question 13, please discuss your preference for determination of FOV with display concept. Would you prefer that the FOV be pilot selectable and determined based upon pilot preference or engineered into the system to change as a function of flight?

____

____

____

____

____

15. If you had to select between two different FOVs that may be pilot selectable, which two FOVs would you choose?______________________

16. Based on response in question 15, please indicate your rationale for choosing these two FOVs.

17. Please discuss the advantages and/or positives associated with this primary flight display concept.

18. Please discuss the disadvantages and/or negatives associated with this primary flight display concept.

19. What improvements would you suggest for this primary flight display concept?

Size-D Display Evaluations

Based on the *Size-D primary flight display* that was presented to you during the flight evaluations.

20. Please evaluate the ease of performing a landing approach.

|____|____|____|____|____|____|____|____|____|____|

Very hard	Somewhat hard	Neutral	Somewhat easy	Very easy

21. Please evaluate the ease of interpreting airspeed information.

|____|____|____|____|____|____|____|____|____|____|

Very hard	Somewhat hard	Neutral	Somewhat easy	Very easy

22. Please evaluate the ease of interpreting altitude information.

|____|____|____|____|____|____|____|____|____|____|

Very hard	Somewhat hard	Neutral	Somewhat easy	Very easy

23. Please evaluate the ease of interpreting flight-path vector.

|____|____|____|____|____|____|____|____|____|____|

Very hard	Somewhat hard	Neutral	Somewhat easy	Very easy

24. Please evaluate the ease of interpreting vertical speed information.

|____|____|____|____|____|____|____|____|____|____|

Very hard	Somewhat hard	Neutral	Somewhat easy	Very easy

25. Please evaluate the ease of interpreting ILS/precision approach deviation indicators.

|____|____|____|____|____|____|____|____|____|____|

Very hard	Somewhat hard	Neutral	Somewhat easy	Very easy

26. Please evaluate the ease of predicting flight path.

|____|____|____|____|____|____|____|____|____|____|

Very hard	Somewhat hard	Neutral	Somewhat easy	Very easy

27. Please evaluate this display for ease of maintaining spatial awareness while flying the approach.

|____|____|____|____|____|____|____|____|____|____|

Very hard	Somewhat hard	Neutral	Somewhat easy	Very easy

Comments (Questions 20–27): ____

____

____

28. Evaluate the ease of maintaining situational awareness. Note: One could define situation awareness as *"...the pilot has an integrated understanding of the factors that will contribute to the safe flying of the aircraft under normal or non-normal conditions."*

|____|____|____|____|____|____|____|____|____|____|

Very hard	Somewhat hard	Neutral	Somewhat easy	Very easy

Comments____

____

____

29. Please indicate the FOV that you thought most preferable (and selected during experimental test runs) for the Dallas/Fort Worth database.

Comments____

____

____

30. Please evaluate how the FOV you selected (indicated "pilot choice" below) affected how confident you were in your knowledge of your **separation from terrain**.

Pilot choice |____|
Low High

31. Please evaluate how the FOV you selected (indicated "pilot choice" below) affected how confident you were in your knowledge of your aircraft's **flight parameters and flight vector**.

Pilot choice |____|
Low High

32. Please provide any comments regarding whether the FOV requirements would change as a function of phase of flight. Example: "I would like to use 90 FOV for cruise but unity FOV for approach."

____
____
____
____
____

33. Based on your comments in question 32, please discuss your preference for determination of FOV with display concept. Would you prefer that the FOV be pilot selectable and determined based upon pilot preference or engineered into the system to change as a function of flight?

____
____
____
____
____

34. If you had to select between two different FOVs that may be pilot selectable, which two FOVs would you choose?________________________________

35. Based on response in question 34, please indicate your rationale for choosing these two FOVs.

____
____
____
____
____

36. Please discuss the advantages and/or positives associated with this primary flight display concept.

37. Please discuss the disadvantages and/or negatives associated with this primary flight display concept.

38. What improvements would you suggest for this primary flight display concept?

Size-X Display Evaluations

Based on the *Size-X primary flight display* that was presented to you during the flight evaluations.

39. Please evaluate the ease of performing a landing approach.

|____|____|____|____|____|____|____|____|____|____|

Very hard	Somewhat hard	Neutral	Somewhat easy	Very easy

40. Please evaluate the ease of interpreting airspeed information.

|____|____|____|____|____|____|____|____|____|____|

Very hard	Somewhat hard	Neutral	Somewhat easy	Very easy

41. Please evaluate the ease of interpreting altitude information.

|____|____|____|____|____|____|____|____|____|____|

Very hard	Somewhat hard	Neutral	Somewhat easy	Very easy

42. Please evaluate the ease of interpreting flight-path vector.

|____|____|____|____|____|____|____|____|____|____|

Very hard	Somewhat hard	Neutral	Somewhat easy	Very easy

43. Please evaluate the ease of interpreting vertical speed information.

|____|____|____|____|____|____|____|____|____|____|

Very hard | Somewhat hard | Neutral | Somewhat easy | Very easy

44. Please evaluate the ease of interpreting ILS/precision approach deviation indicators.

|____|____|____|____|____|____|____|____|____|____|

Very hard | Somewhat hard | Neutral | Somewhat easy | Very easy

45. Please evaluate the ease of predicting flight path.

|____|____|____|____|____|____|____|____|____|____|

Very hard | Somewhat hard | Neutral | Somewhat easy | Very easy

46. Please evaluate this display for ease of maintaining spatial awareness while flying the approach.

|____|____|____|____|____|____|____|____|____|____|

Very hard | Somewhat hard | Neutral | Somewhat easy | Very easy

Comments (Questions 39–46): ____

____

____

47. Evaluate the ease of maintaining situational awareness. Note: One could define situation awareness as *"...the pilot has an integrated understanding of the factors that will contribute to the safe flying of the aircraft under normal or non-normal conditions."*

|____|____|____|____|____|____|____|____|____|____|

Very hard	Somewhat hard	Neutral	Somewhat easy	Very easy

Comments____

____

____

48. Please indicate the FOV that you thought most preferable (and selected during experimental test runs) for the Dallas/Fort Worth database.

Comments____

____

____

49. Please evaluate how the FOV you selected (indicated "pilot choice" below) affected how confident you were in your knowledge of your **separation from terrain**.

Pilot |____|

choice Low High

50. Please evaluate how the FOV you selected (indicated "pilot choice" below) affected how confident you were in your knowledge of your aircraft's **flight parameters and flight vector**.

Pilot |____|

choice Low High

51. Please provide any comments regarding whether the FOV requirements would change as a function of phase of flight. Example: "I would like to use 90 FOV for cruise but unity FOV for approach."

52. Based on your comments in question 51, please discuss your preference for determination of FOV with display concept. Would you prefer that the FOV be pilot selectable and determined based upon pilot preference or engineered into the system to change as a function of flight?

53. If you had to select between two different FOVs that may be pilot selectable, which two FOVs would you choose?________________________

54. Based on response in question 53, please indicate your rationale for choosing these two FOVs.

55. Please discuss the advantages and/or positives associated with this primary flight display concept.

56. Please discuss the disadvantages and/or negatives associated with this primary flight display concept.

57. What improvements would you suggest for this primary flight display concept?

Generic-Texturing and Photo-Realistic-Texturing Comparisons on Head-Down Primary Flight Display

58. Please evaluate the ease of using the primary flight display with the generic terrain database.

|____|____|____|____|____|____|____|____|____|____|

Very hard	Somewhat hard	Neutral	Somewhat easy	Very easy

59. Please evaluate the ease of using the primary flight display with the photo-realistic terrain database.

|____|____|____|____|____|____|____|____|____|____|

Very hard	Somewhat hard	Neutral	Somewhat easy	Very easy

60. Were you able to judge depth/range and altitude cues with the photo-realistic and generic terrain databases? Please comment on both databases.

____
____
____
____
____

61. Did the geographical features found in the photo-realistic terrain database help orient you during an approach? Please comment on your answer.

____
____
____
____
____

62. During the runway change task, did the photo-realistic terrain database help in acquiring the new runway? Or was acquisition not affected by the type of texturing, photo-realistic or generic, that was used in the terrain database? Please comment on your answer.

63. Please discuss any advantages or positives that the generic terrain database may provide compared to the photo-realistic terrain database display.

64. Please discuss any problems or disadvantages that the generic terrain database did/may present compared to the photo-realistic terrain database display.

Head-Up Display (HUD) Evaluations

65. Based upon your exposure to the different head-up displays (HUDs) concepts, please indicate your OVERALL relative ranking/grading of the HUD concept.

Low Res |____|____|____|____|____|____|____|____|____|____|

0 1 2 3 4 5 6 7 8 9 10

Least desirable HUD — Most desirable HUD

High Res |____|____|____|____|____|____|____|____|____|____|

0 1 2 3 4 5 6 7 8 9 10

Least desirable HUD — Most desirable HUD

Generic |____|____|____|____|____|____|____|____|____|____|

0 1 2 3 4 5 6 7 8 9 10

Least desirable HUD — Most desirable HUD

Photo |____|____|____|____|____|____|____|____|____|____|

0 1 2 3 4 5 6 7 8 9 10

Least desirable HUD — Most desirable HUD

66. Please discuss your rationale in determining the overall evaluation in item 65.

____

____

____

____

____

67. Please rate the ease of acquiring the outside window view with the HUD resolution concept.

68. Please provide your agreement to each of the following statements concerning the use of the HUD resolution concept with head-down synthetic vision display (please mark on bar).

HUD resolution concept provides sufficient situational awareness without the addition of a head-down display.

Disagree	Somewhat disagree	Somewhat agree	Agree

HUD resolution concept provides sufficient situational awareness only if accompanied by head-down display.

Disagree	Somewhat disagree	Somewhat agree	Agree

HUD resolution concept should not be used and does not provide any additional situational awareness enhancement than that provided by head-down display.

Disagree	Somewhat disagree	Somewhat agree	Agree

69. Please provide your rationale for the statement agreement ratings you provided previously. For example, I disagreed that HUD resolution concept...because....

70. Please provide any comments or suggestions that may help us evaluate the HUD resolution concept. However, please confine your comments to the display concept and do not comment on the symbology set.

71. Please evaluate the ease of using the HUD with the generic terrain database.

Very hard	Somewhat hard	Neutral	Somewhat easy	Very easy

72. Please evaluate the ease of using the HUD with the photo-realistic terrain database.

Very Hard	Somewhat Hard	Neutral	Somewhat Easy	Very Easy

73. Were you able to judge depth/range and altitude cues with the photo-realistic and generic terrain databases when they were presented on the HUD? Please comment on both databases.

74. Did the geographical features found in the photo-realistic terrain database help orient you during an approach? Please comment on your answer.

75. Please discuss any advantages or positives that the generic terrain database may provide compared to the photo-realistic terrain database display when presented on the HUD.

76. Please discuss any problems or disadvantages that the generic terrain database did/may present compared to the photo-realistic terrain database display when presented on the HUD.

Appendix C

Postflight Questionnaire Data and Pilot Comments

Tabular Results From Questionnaire

Table C1. Pilot Ratings Using Response Key 1

Numerical response key 1

Numerical value	1	2	3	4	5	6	7	8	9	10
Associated word	Very hard		Somewhat hard		Neutral	Neutral		Somewhat easy		Very easy

Questions regarding each HDD size evaluated using key 1													
Question		Display	Pilot number						Max	Min	Ave	Stdev
			1	2	3	4	5	6				
1	Evaluate the ease of performing the landing approach.	Size-A	3	7	6	7	5	8	8.00	3.00	6.00	1.79
		Size-D	8.5	8	8	5	6	9	9.00	5.00	7.42	1.56
		Size-X	10	9	9	10	9	10	10.00	9.00	9.50	0.55
2	Evaluate the ease of interpreting air-speed information.	Size-A	5.5	8	5	6	9	8	9.00	5.00	6.92	1.63
		Size-D	6	8	8	10	3	9	10.00	3.00	7.33	2.50
		Size-X	9		10	10	3	10	10.00	3.00	8.40	3.05
3	Evaluate the ease of interpreting altitude information.	Size-A	7	8	5	6	7	8	8.00	5.00	6.83	1.17
		Size-D	6	8	8	10	3	9	10.00	3.00	7.33	2.50
		Size-X	8		10	10	3	10	10.00	3.00	8.20	3.03
4	Evaluate ease of interpreting flight-path vector.	Size-A	3	4	7	10	8	10	10.00	3.00	7.00	2.97
		Size-D	6	6	9	10	8	9	10.00	6.00	8.00	1.67
		Size-X	7.5	8	9	10	9	10	10.00	7.50	8.92	1.02
5	Evaluate the ease of interpreting vertical speed information.	Size-A	8.5	8	6	6	8	9	9.00	6.00	7.58	1.28
		Size-D	6	5	8	1	8	9	9.00	1.00	6.17	2.93
		Size-X	8		10	6	8	10	10.00	6.00	8.40	1.67
6	Evaluate the ease of interpreting ILS/ precision approach deviation indicators.	Size-A	7.5	8	6	4	7	6	8.00	4.00	6.42	1.43
		Size-D	9	8		5	8	9	9.00	5.00	7.80	1.64
		Size-X	9			4	8	10	10.00	4.00	7.75	2.63
7	Evaluate ease of predicting flight path.	Size-A	5.5	4	6	10	7	9	10.00	4.00	6.92	2.25
		Size-D	8	6	6	10	7	9	10.00	6.00	7.67	1.63
		Size-X	8	9	8	10	8	10	10.00	8.00	8.83	0.98
8	Evaluate this display for ease of maintaining spatial awareness while flying the approach.	Size-A	3.5	8	6	7	6		8.00	3.50	6.10	1.67
		Size-D	10	7	9	8	7	9	10.00	7.00	8.33	1.21
		Size-X	10	9	10	9	8	10	10.00	8.00	9.33	0.82
9	Evaluate the ease of maintaining situational awareness.	Size-A	7.5	8	6	7	4	9	9.00	4.00	6.92	1.74
		Size-D	10	8	8	7	4	9	10.00	4.00	7.67	2.07
		Size-X	10	9	10	8	5	10	10.00	5.00	8.67	1.97

Table C1. Concluded

Questions regarding generic versus photo-realistic terrain texturing using key 1													
Question		Terrain	Pilot number						Max	Min	Ave	Stdev
			1	2	3	4	5	6				
16	Please evaluate the ease of using the primary flight display with the generic terrain database.	Generic	8.5	8	8	4	8	5	8.50	4.00	6.92	1.91
17	Please evaluate the ease of using the primary flight display with photo-realistic terrain database.	Photo-realistic	9	9	10	7	7	9	10.00	7.00	8.50	1.22
20	Please evaluate the ease of using the HUD with generic terrain database.	Generic		8	9	3	9	8	9.00	3.00	7.40	2.51
21	Please evaluate the ease of using the HUD with the photo-realistic terrain database.	Photo-realistic		8	10	9	7	9	10.00	7.00	8.60	1.14

Table C2. Pilot Ratings Using Response Key 2

Numerical response key 2

Numerical value	1	2	3	4	5
Associated word	Low				High

Questions regarding how FOV selection affected knowledge of terrain, flight parameters, and flight vector													
Question		Display	Pilot number						Max	Min	Ave	Stdev
			1	2	3	4	5	6				
11	Please evaluate how the FOV you selected affected how confident you were in your knowledge of your separation from terrain.	Size-A	2.5	4	3	3	2	4	4.00	2.00	3.08	0.80
		Size-D	4	5	3	3	3	4	5.00	3.00	3.67	0.82
		Size-X	4	4	4	3	3	4	4.00	3.00	3.67	0.52
12	Please evaluate how the FOV you selected affected how confident you were in your knowledge of flight parameters and flight vector.	Size-A	3.5	5	3	4	3	4	5.00	3.00	3.75	0.76
		Size-D	4	2	3	5	3	4	5.00	2.00	3.50	1.05
		Size-X	4	4	4	5	4	4	5.00	4.00	4.17	0.41

Table C3. Pure Numerical Responses to FOV Selection

Numerical responses from pilots regarding FOV selection													
Question		Display	Pilot number						Max	Min	Ave	Stdev
			1	2	3	4	5	6				
10	Please indicate the FOV that you thought most preferable.	Size-A	30	12	30	30	60	30	60.00	12.00	32.00	15.49
		Size-D	30	14.6	30	30	60	30	60.00	14.60	32.43	14.84
		Size-X	30	22.6	22.6		60	30	60.00	22.60	33.04	15.52
15-1	If you had to select between two different FOVs that may be pilot selectable, which two FOVs would you choose (1st choice).	Size-A	12.6	12.6	30	30	12.6	30	30.00	12.60	21.30	9.53
		Size-D	30	14.6	30	30	60	30	60.00	14.60	32.43	14.84
		Size-X	30	22.6	22.6	30	60	30	60.00	22.60	32.53	13.94
15-2	If you had to select between two different FOVs that may be pilot selectable, which two FOVs would you choose (2nd choice).	Size-A	60	45	60	90	60	60	90.00	45.00	62.50	14.75
		Size-D	60	45	40	90	14.6	60	90.00	14.60	51.60	25.15
		Size-X	60	45	30	120	22.6	60	120.00	22.60	56.27	34.76

Table C4. Pilot Ratings Using Response Key 3

Numerical response key 3

Numerical value	1	2	3	4	5	6	7	8	9	10
Associated word	Least desirable									Most desirable

Questions regarding relative ranking of HUD concepts									
Question		Pilot 1	Pilot 2	Pilot 3	Pilot 4	Pilot 5	Pilot 6	Mean	Stdev
18	Based on your exposure to the different HUD concepts, please indicate your overall relative ranking/grading of the generically textured HUD concept.	8	5	7	3	8	6	6.2	1.9
19	Based on your exposure to the different HUD concepts, please indicate your overall relative ranking/grading of the photo realistically textured HUD concept.	9	7	9	7	6	8	7.7	1.2

Table C5. Pilot Ratings Using Response Key 4

Numerical response key 4

Numerical value	1	2	3	4
Associated word	Disagree	Somewhat disagree	Somewhat agree	Agree

Questions regarding the NASA Opaque HUD concept viability									
Question		Pilot 1	Pilot 2	Pilot 3	Pilot 4	Pilot 5	Pilot 6	Mean	Stdev
22	The NASA Opaque HUD concept provides sufficient situational awareness without the addition of the head-down display.		2	3	3	3	3	2.8	0.4
23	The NASA Opaque HUD concept provides sufficient situational awareness only if accompanied by head-down display.		2	2	1	1	2	1.6	0.5
24	The NASA Opaque HUD concept should not be used and does not provide any additional situational awareness enhancement than that provided by a HDD.		1	1	1	1	1	1.0	0.0

Graphical Presentation of Subjective Ratings

Figures C1 through C17 display the subjective ratings from the questionnaire.

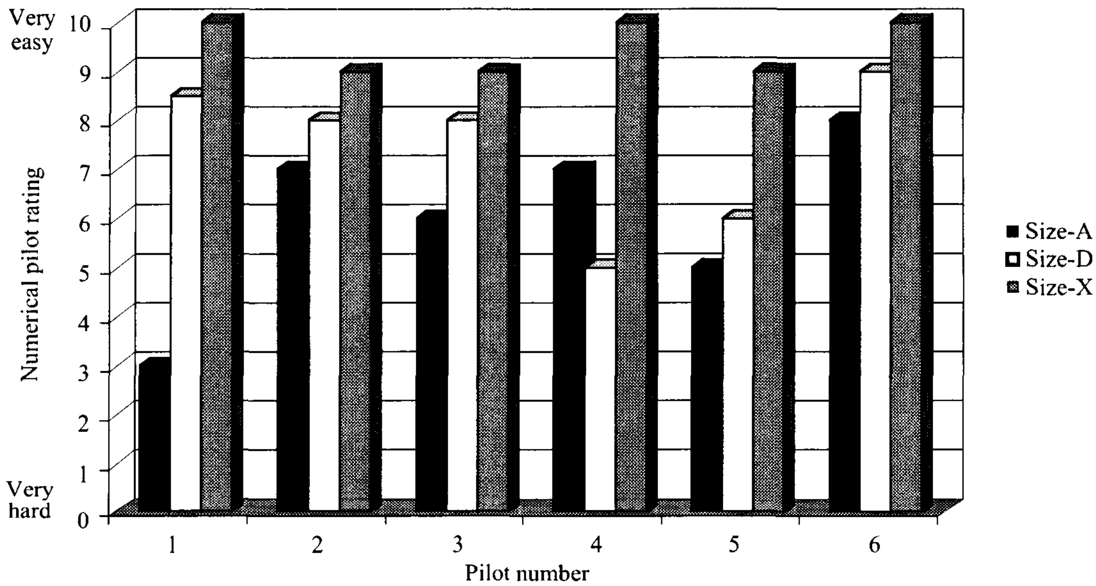

Figure C1. Response to question 1: Evaluate ease of performing landing approach.

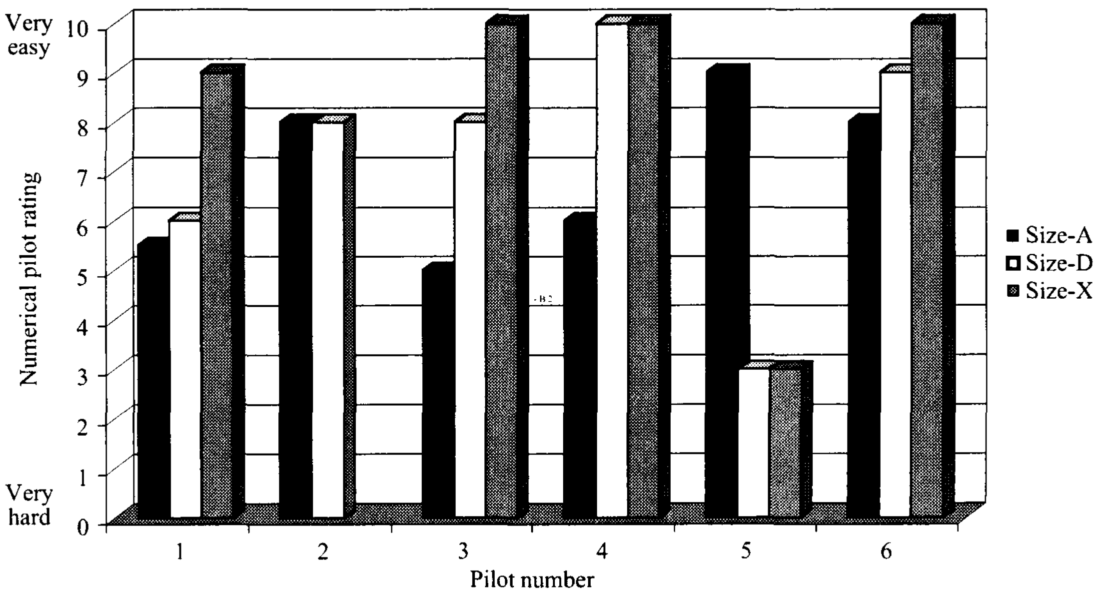

Figure C2. Response to question 2: Evaluate ease of interpreting airspeed information.

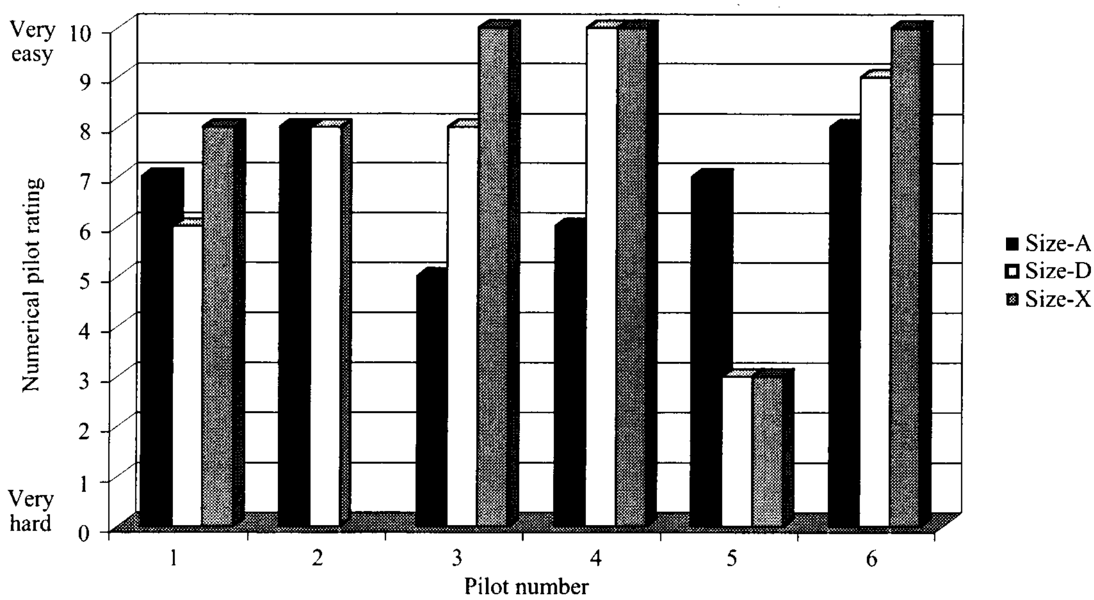

Figure C3. Response to question 3: Evaluate ease of interpreting altitude information.

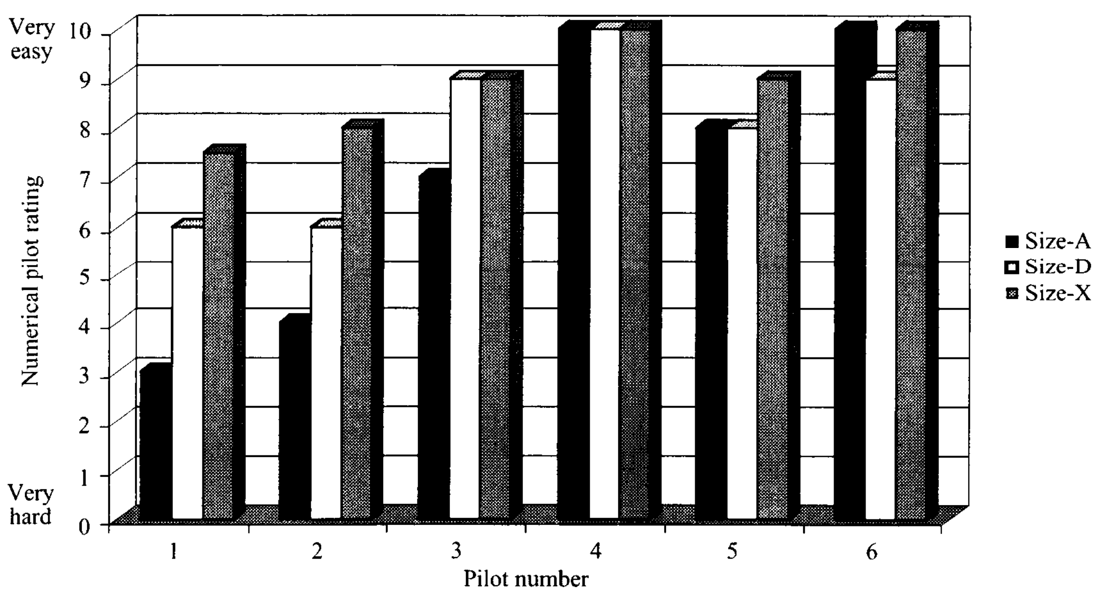

Figure C4. Response to question 4: Evaluate ease of interpreting the flight-path vector.

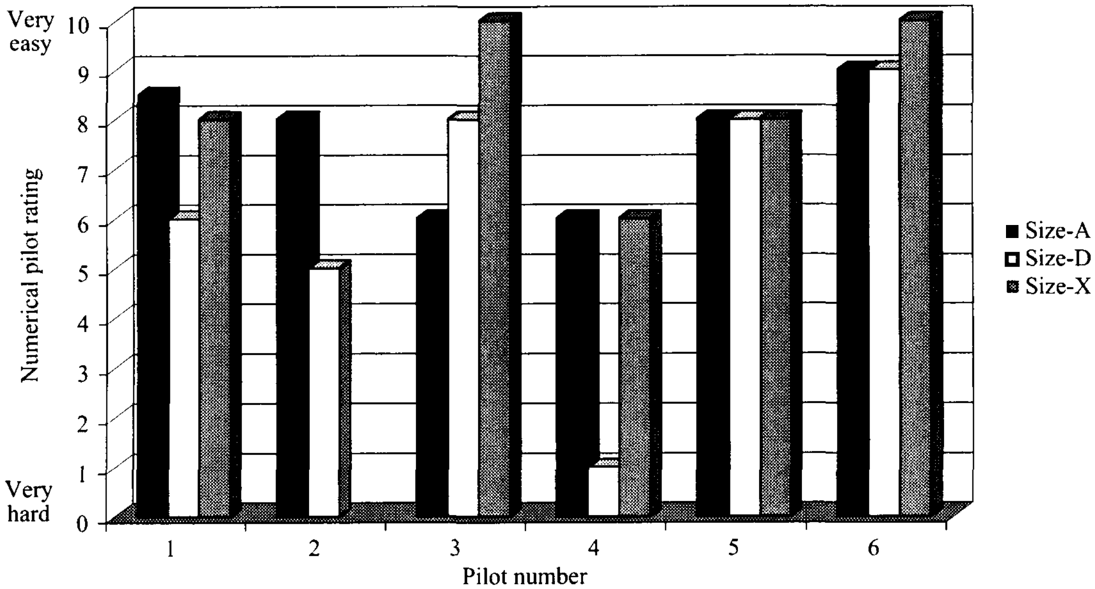

Figure C5. Response to question 5: Evaluate ease of interpreting vertical speed information.

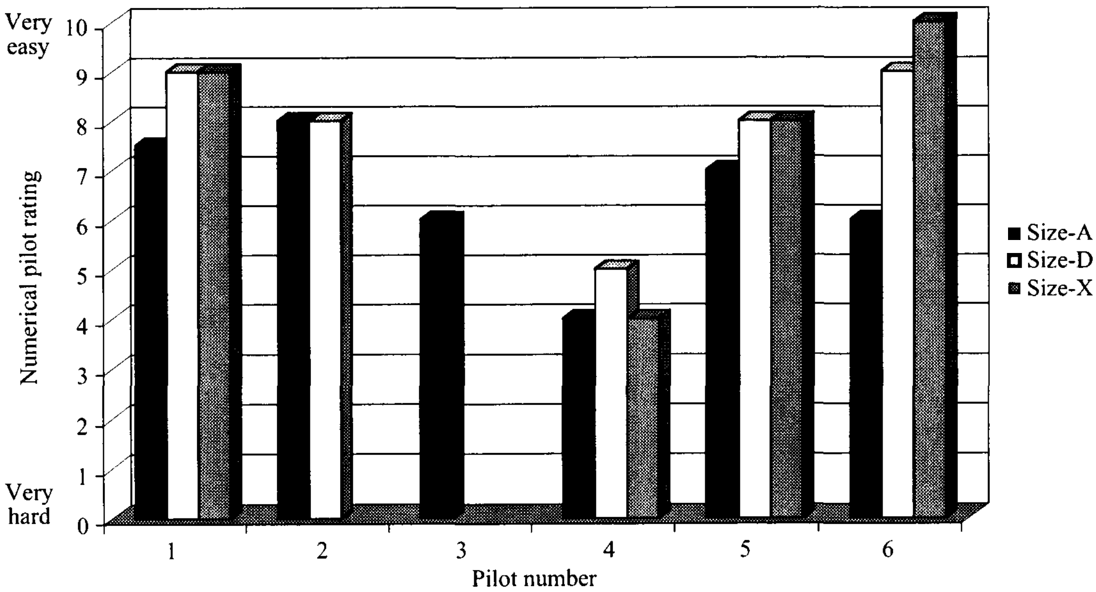

Figure C6. Response to question 6: Evaluate ease of interpreting ILS/precision approach deviation indicators.

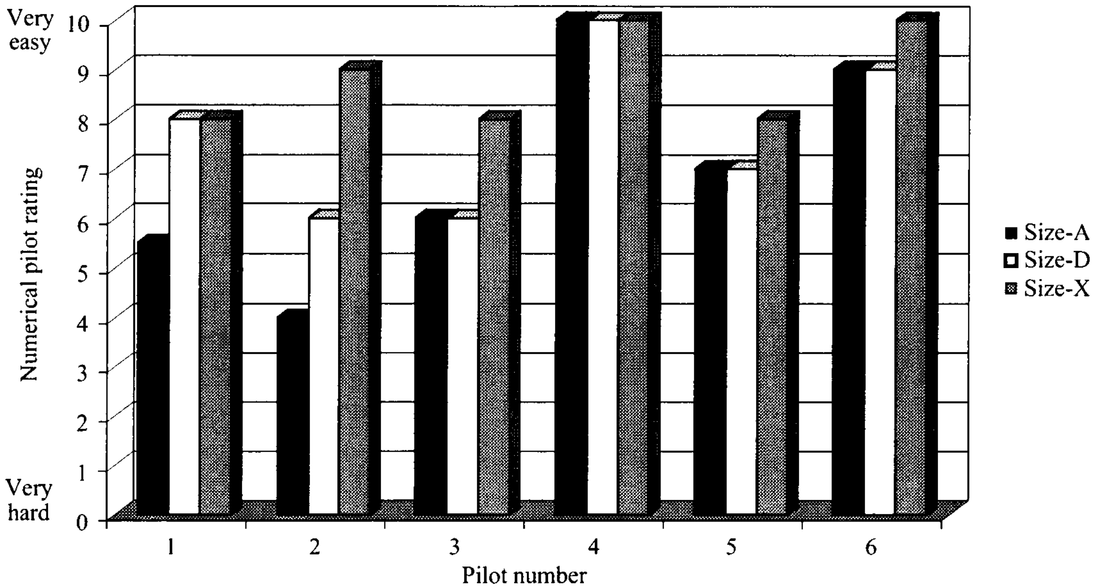

Figure C7. Response to question 7: Evaluate ease of predicting flight path.

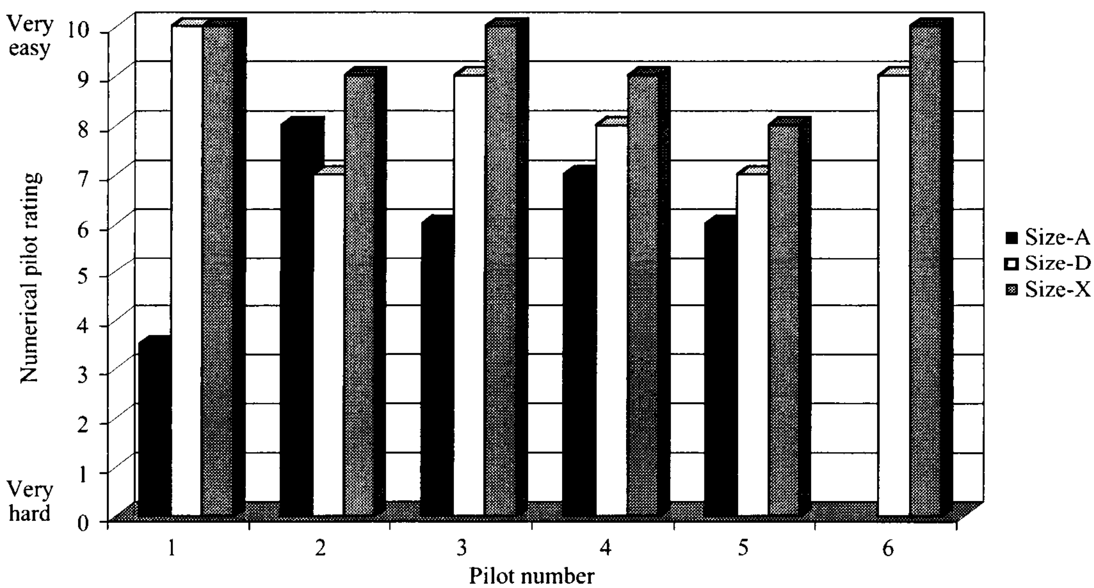

Figure C8. Response to question 8: Evaluate this display for maintaining spatial awareness while flying the approach.

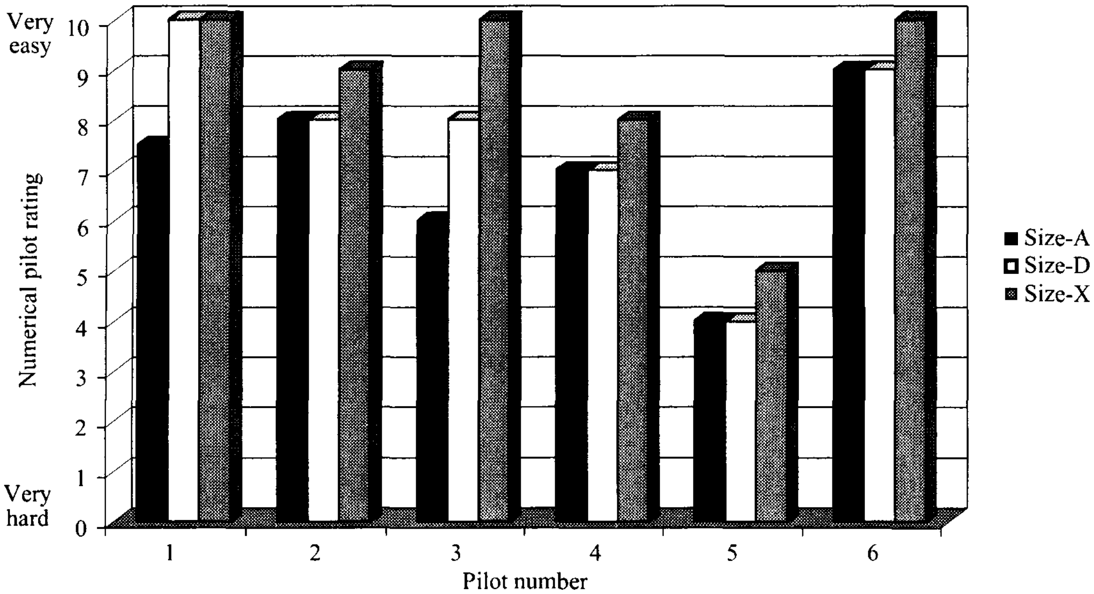

Figure C9. Response to question 9: Evaluate ease of maintaining situational awareness.

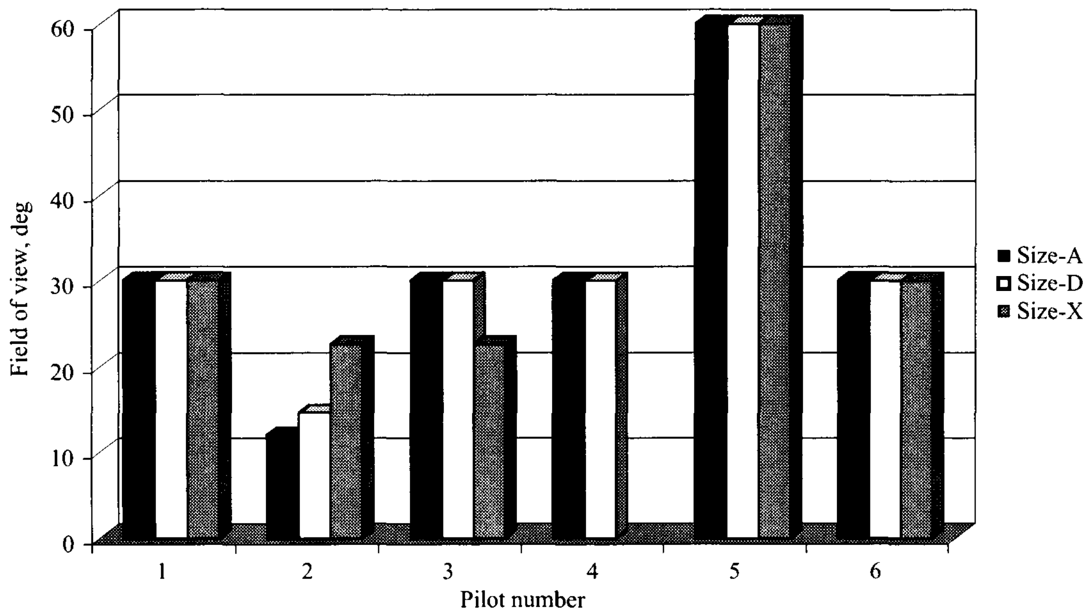

Figure C10. Response to question 10: Please indicate FOV that you thought most preferable.

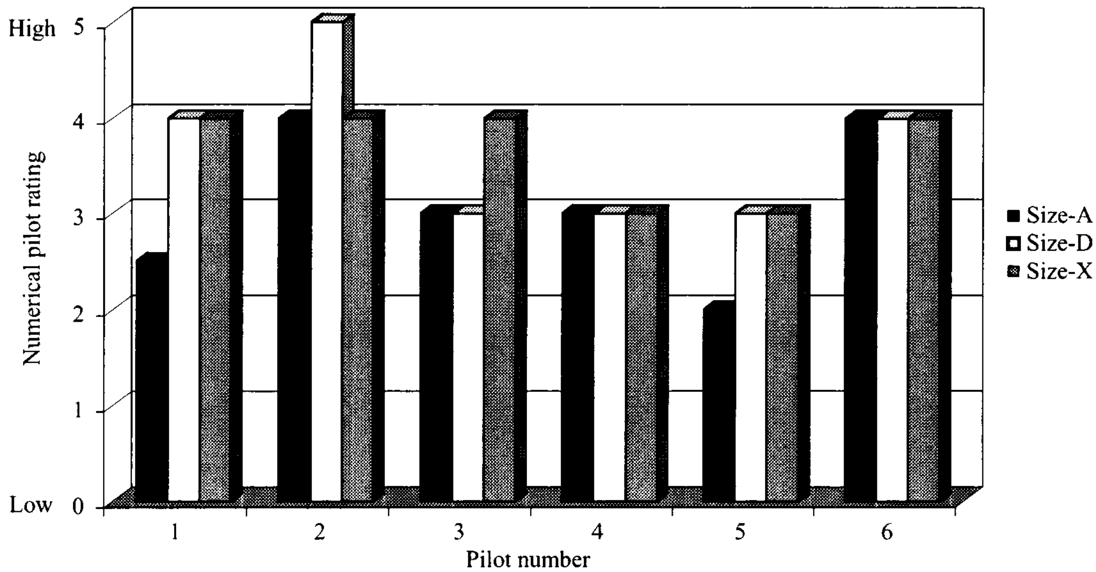

Figure C11. Response to question 11: Please evaluate how FOV you selected affected how confident you were in your knowledge of your separation from terrain.

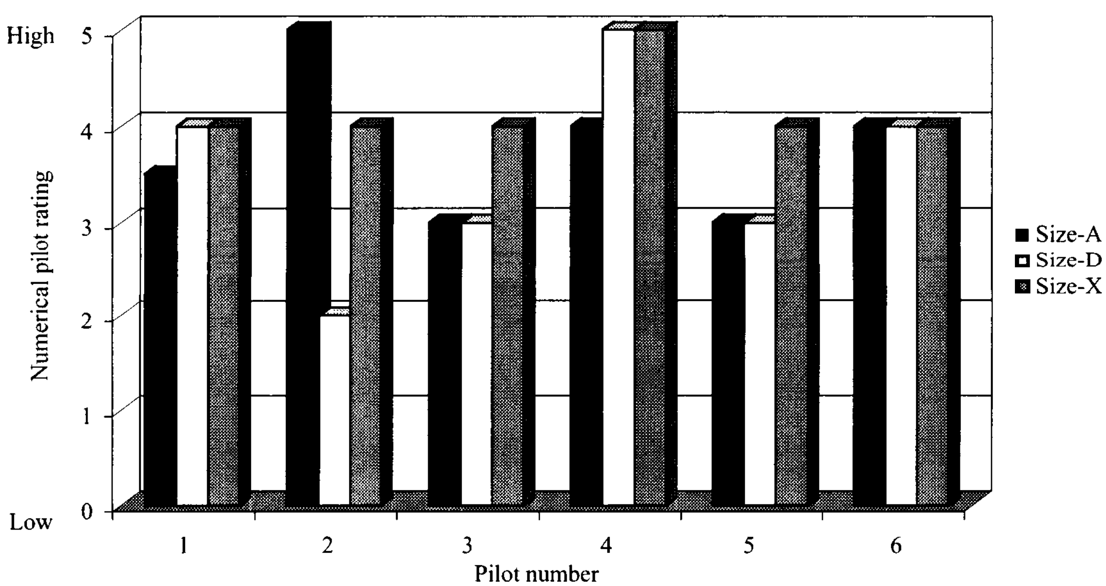

Figure C12. Response to question 12: Please evaluate how FOV you selected affected how confident you were in your knowledge of flight parameters and flight-path vector.

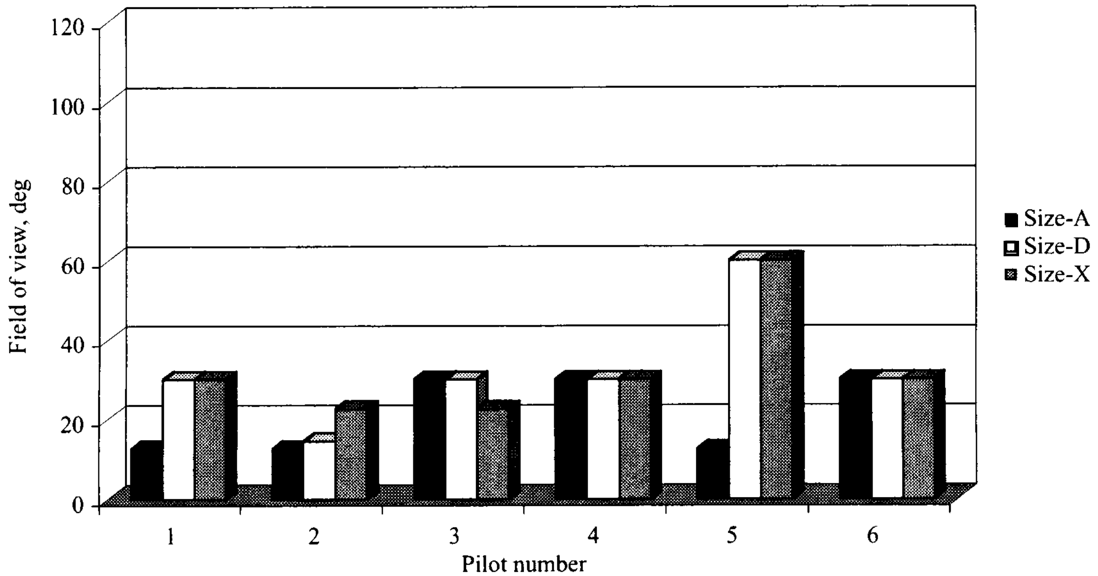

Figure C13. Response to question 15-1: If you had to select between two different FOVs that may be pilot selectable, which two FOVs would you choose (first choice)?

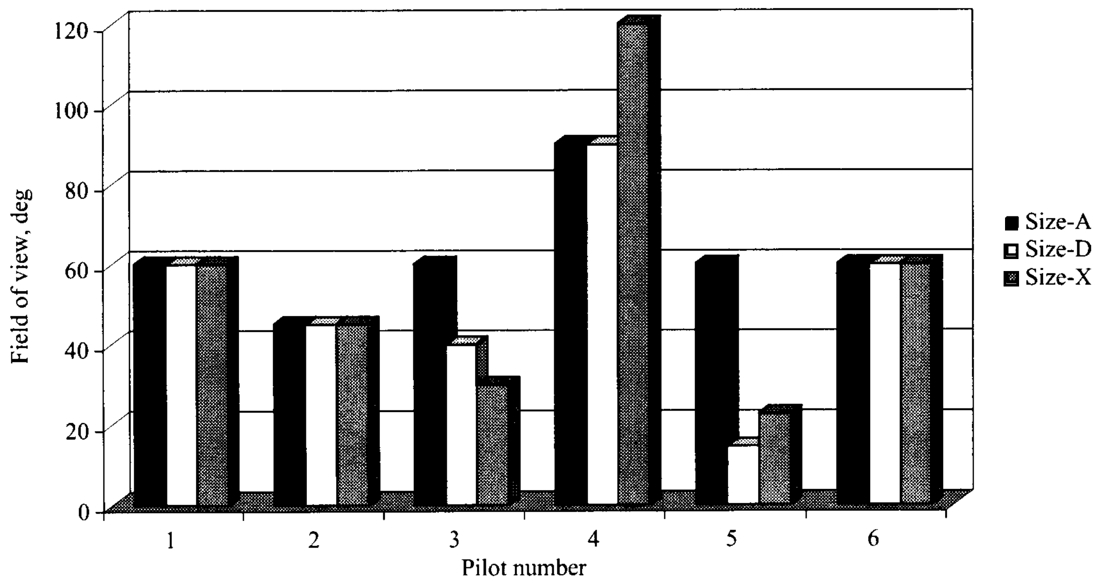

Figure C14. Response to question 15-2: If you had to select between two different FOVs that may be pilot selectable, which two FOVs would you choose (second choice)?

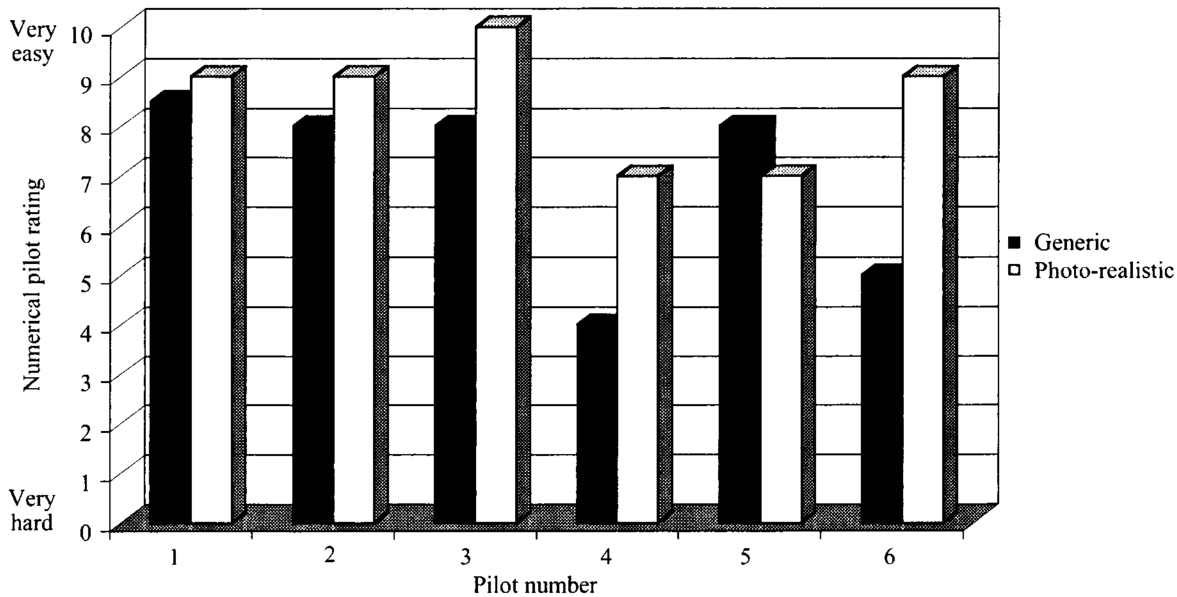

Figure C15. Response to questions 16 and 17: Please evaluate ease of using primary flight display with generic and photo realistic texturing.

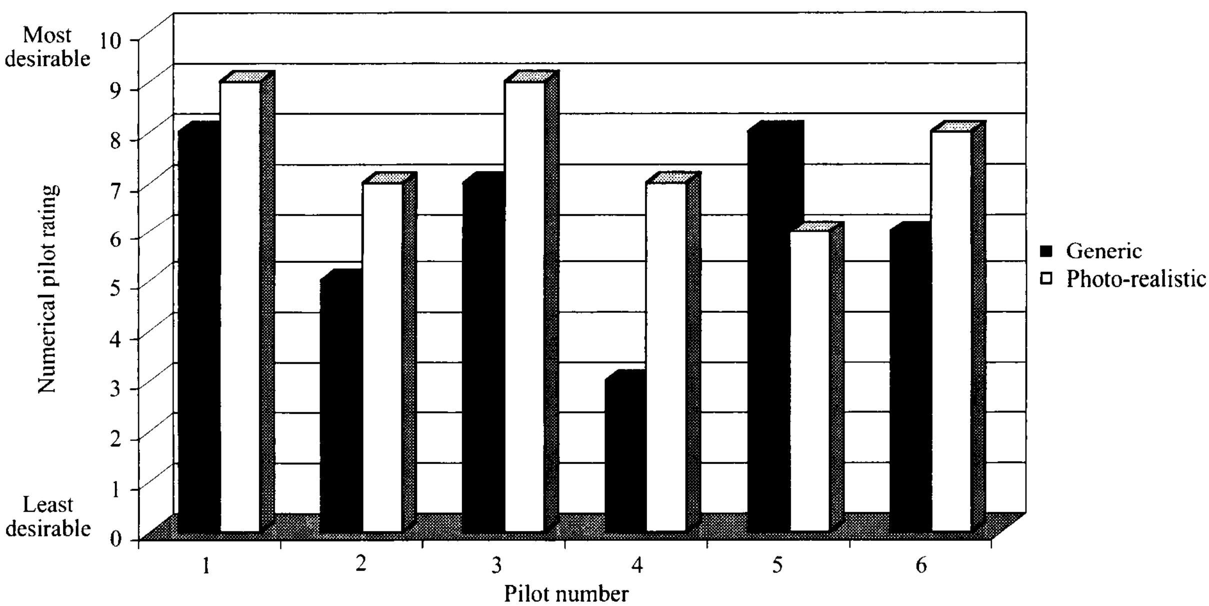

Figure C16. Response to questions 18 and 9: Based on your exposure to different HUD concepts, please indicate your overall relative ranking/grading of the generically and photo-realistic textured HUD concepts.

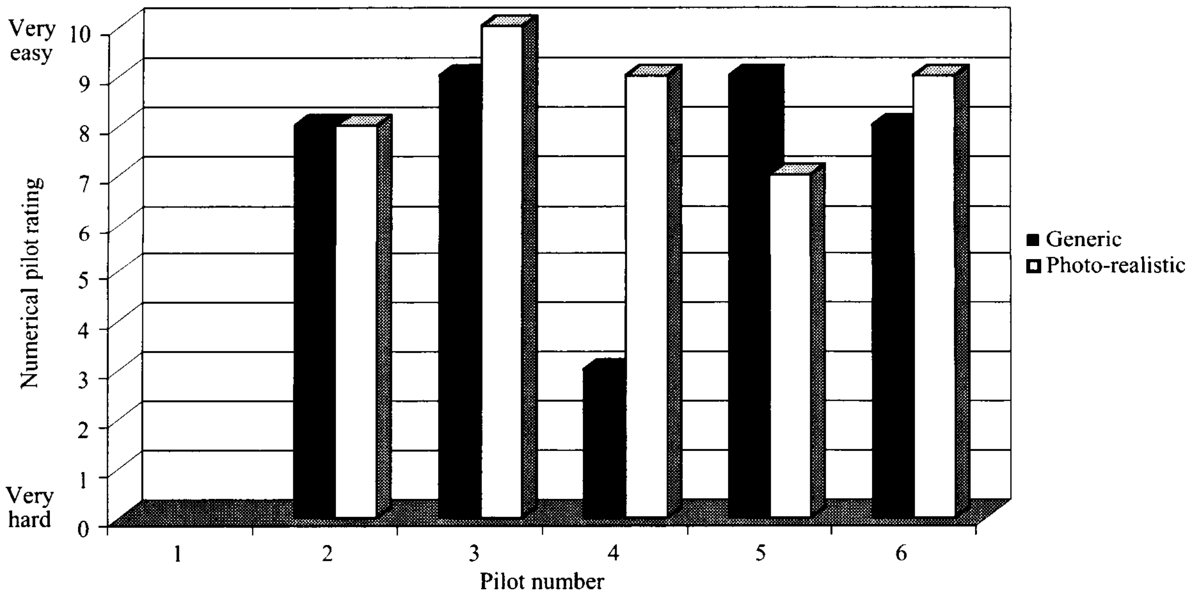

Figure C17. Response to questions 20 and 21: Please evaluate ease of using HUD with generic and photo realistic terrain databases.

Pilot Comments

Pilots were asked to provide written comments* for various sections of the questionnaire. The sections asking for written comments were as follows: All references to question numbers are for tables C1 and C3. Pilot comments are provided subsequently that refer to the items in the table (e.g., if a pilot was providing comments for SA, the note is listed re 2, followed by the written comment).

For each display size, the following areas for comment were provided:

1. Comments for questions 1 through 8
2. In association with question 9 (re: SA)
3. In association with question 10 (re: FOV)
4. Comments regarding whether the FOV requirements would change as a function of phase of flight
5. Comments regarding automated and pilot selectable FOVs
6. Comments regarding rationale for choosing the two fields of view chosen in question 15.
7. Discuss the advantages and/or positives associated with this primary flight display concept.
8. Discuss the disadvantages and/or negatives associated with this primary flight display concept.
9. What improvements would you suggest for this primary flight display concept?

For the comparison of generic vs. photo-realistic terrain-texturing techniques for the HDD, the following areas for comment were provided:

10. Were you able to judge depth, range and altitude cues with the photo-realistic and generic terrain databases?
11. Did the geographical features found in the photo-realistic terrain database help orient you during an approach?
12. During the runway change task, did the photo-realistic terrain database help in acquiring the new runway?
13. Please discuss any advantages or positives that the generic terrain database may provide compared to the photo-realistic terrain database.
14. Please discuss any disadvantages or problems that the generic terrain database did or may present compared to the photo-realistic terrain database.

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* (?) Denotes words lost in transcription.

For the HUD evaluations, the following areas were provided for comment:

15. Please discuss your overall ranking of the two HUD concepts (i.e., generic or photo-realistic).
16. Please rate the ease of acquiring the outside window view with the HUD.
17. Please provide your rationale for the statement agreement ratings (questions 22, 23, and 24).
18. Please provide any comments or suggestions that may help evaluate the NASA Opaque HUD concept in future evaluations.
19. Were you able to judge depth, range and altitude cues with the generic photo-realistic terrain databases when presented on the HUD?
20. Did the geographical features found in the photo-realistic terrain database help orient you during the approach.
21. Please discuss any advantages or positives that the generic terrain database may provide compared to the photo-realistic terrain database when presented on the HUD.
22. Please discuss any problems or disadvantages that the generic terrain database did/may present compared to the photo-realistic terrain database when presented on the HUD.

Pilot 1 Comments

Re 1 Size-A:	The size-A is too small to be useful, and I found myself constantly using the HUD.
Re 3 Size-A:	I did not change the FOV because I relied on the HUD.
Re 4 Size-A:	I would use 90/60 for the downwind and base, then unity or 30 for final.
Re 5 Size-A:	Pilot selectable absolutely but instead of FOV changes every 5°, give me a choice of unity/30/45/60/90.
Re 6 Size-A:	There are tradeoffs between 90° and 45°.
Re 7 Size-A:	Advantage is that it allows me to actually "see" the runway.
Re 8 Size-A:	Disadvantage—size-A is too small.
Re 9 Size-A:	Make the selectable FOV touch screen bigger and give me the unity/3/45/60/90 selectable.
Re 1 Size-D:	The bigger size is better and the positioning of the "tactical" and "strategic" displays side by side is better than with the size-A.
Re 2 Size-D:	See comment above (Re 1, size-D). It was easy to switch my attention back and forth from the displays.
Re 3 Size-D:	30° was a tradeoff between 45 and unity.
Re 4 Size-D:	I would use 90/60 for the downwind and base, then unity or 30 for final.
Re 5 Size-D:	Pilot selectable.
Re 6 Size-D:	Tradeoffs between unity and 90.
Re 7 Size-D:	The side-by-side positioning of the displays is excellent.
Re 8 Size-D:	Negative—the round dial presentations of airspeed, altitude, and vertical speed are easier to interpret.
Re 9 Size-D:	Round dial displays for primary instruments and bigger FOV touch pads.

Re 1 Size-X:	Side-by-side displays are excellent.
Re 2 Size-X:	Side-by-side displays are excellent.
Re 4 Size-X:	I would use 90/60 for the downwind and base, then unity or 30 for final.
Re 5 Size-X:	Pilot selectable.
Re 6 Size-X:	Tradeoff between unity and 90°.
Re 7 Size-X:	Advantage—side-by-side display and the bigger size.
Re 8 Size-X:	Negative—the compound compass rose display can be disorientating, and no round dial displays for the primary instruments.
Re 9 Size-X:	Round compass rose and round dial instruments.
Re 10:	Photo-realistic is better.
Re 15:	The photo-realistic was easier for determining relative position and depth perception.
Re 19:	Photo-realistic is better.
Re 20:	Absolutely, that was excellent!
Re 21:	None.
Re 22:	It did not orient me as well as the photo-realistic did.

Pilot 2 Comments

Re 1 Size-A:	Flight path and flight-path vector were off screen while turning in my preferred FOV (unity).
Re 2 Size-A:	With the A/S, alt., and VSI in close proximity, it was easier.
Re 3 Size-A:	Would like to be able to tilt and pan.
Re 4 Size-A:	I would pick unity with the ability to pan and tilt.
Re 5 Size-A:	Option to control or follow FPV or tilt and pan pilot selectable.
Re 6 Size-A:	Unity with the FPV on screen. 45° to accommodate most intercept angles.
Re 7 Size-A:	Close proximity of primary flight instruments to SV display. Familiar instrument displays (round dials).
Re 8 Size-A:	Limited by FOV and inability to tilt and pan.
Re 9 Size-A:	See above.
Re 1 Size-D:	Bigger FOV easier than size-A display.
Re 4 Size-D:	No threat terrain in the DFW area. I would like to evaluate in mountainous area.
Re 5 Size-D:	Auto to follow FPV or manual (pilot) selectable tilt and pan.
Re 6 Size-D:	Same as above.
Re 7 Size-D:	Same instrument display? Tapes on MD11, Fokker 100.
Re 9 Size-D:	Ability to tilt and pan.
Re 1 Size-X:	Larger FOV enabled FPV to be on screen.

Re 4 Size-X:	Same as previous comments for size-A and size-D. (I would pick unity with the ability to pan and tilt.)
Re 5 Size-X:	Same as previous.
Re 6 Size-X:	Same as previous.
Re 7 Size-X:	Wider FOV.
Re 8 Size-X:	Better display of VSI.
Re 10:	Not very well.
Re 11:	Yes, the airport buildings (terminal) and (?) were recognizable.
Re 12:	Yes, the photo-realistic helped.
Re 13:	No advantages.
Re 14:	No problems, just not as informative.
Re 15:	Not much (?) with no high-threat terrain.
Re 16:	Easy.
Re 17:	I still use raw (?) reference especially during runway changes.
Re 19:	Not very good estimates of either.
Re 20:	DFW airport buildings, runways, etc.
Re 21:	Less distracting from symbology.
Re 22:	None noted.

Pilot 3 Comments

Re 1 Size-A:	This display could not be used in U (unity) because the FOV was too small. Lack of speed and altitude tapes a major negative.
Re 2 Size-A:	Better than today's basic systems, but I think we should aim higher. Can easily make mistake with this size in small percentage of tasks; should have system in which a mistake is very rare.
Re 3 Size-A:	With any less than 30, you would not have enough world and symbology to maintain good SA.
Re 4 Size-A:	This one should be RNP based. The steering cue should show RNP (i.e., .3 as green, 2X RNP area amber, and outside obstacle terrain as red outside of 2X).
Re 5 Size-A:	Engineered with pilot hands on override capability.
Re 6 Size-A:	Need three 30/60/90 if possible. This display is so small wider view is necessary, even though it is difficult to watch.
Re 7 Size-A:	Adds terrain/obstacle/real world to what we have now. Biggest positive is FPV and steering (tunnel).
Re 8 Size-A:	Speed tape and altitude tape are missing. Driving (?) look distance to cross-check.
Re 9 Size-A:	Make it bigger, add tapes, recenter FOV and tapes around FPV.

Re 1 Size-D:	Better than size-A but still could not use unity very well. World view better and probably minimally useable with high rate of success (i.e., fewer mistakes).
Re 2 Size-D:	Although the real world (synthetic) is not as easy to see on this display, the information symbology is easier to use because it is closer to the FPV.
Re 3 Size-D:	Any less caused loss of too much vertical. When on downwind and base, 60 better because it brought corners of tunnel together and made flying easier.
Re 4 Size-D:	This display should be RNP based. The steering cue should show RNP (i.e., .3 as green, 2X RNP area amber, and outside obstacle terrain as red outside of 2X).
Re 5 Size-D:	Engineered with pilot hands on override capability.
Re 6 Size-D:	This display provides good SA for most cases. Unity would be desired if more down vertical were available.
Re 7 Size-D:	Big improvement over size-A and what I would grade as acceptable. Should be closer to pilot to see better. I like tapes, FPV, and most things about this one.
Re 8 Size-D:	Disadvantages are no occlusion logic.
Re 9 Size-D:	Pitch ladder, floating tapes, occlusion logic, RNP tunnels.
Re 1 Size-X:	This one is obviously the best of the three (A, D, X). Prime advantage—can fly much more accurately because display is bigger and easier to see. World seemed closer to reality.
Re 2 Size-X:	This display is by far the safest in my view. It is easy to determine what you are looking at without study. Very intuitive.
Re 3 Size-X:	Field of view should center on FPV, bank indicator too far above area of FPV. Need occlusion logic and more color—i.e., magenta is desired track, so deviation diamonds should be magenta.
Re 4 Size-X:	This one should be RNP based. The steering cue should show RNP (i.e., .3 as green, 2X RNP area amber, and outside obstacle terrain as red outside of 2X).
Re 5 Size-X:	Engineered with pilot hands on override capability.
Re 6 Size-X:	30 in this unity gives a good view. I would like "snap look" capability.
Re 7 Size-X:	Advantages: (1) Large enough to see world intuitively, (2) with photo-realistic texture very real feeling, (3) easier to see surrounding terrain.
Re 8 Size-X:	Not head up, symbology too spread out, no pitch ladders, no snap look, too far from pilot's eye.
Re 9 Size-X:	(1) Pitch ladder, (2) occlusion logic, (3) RNP tunnels, (4) must have RNP display and color. This display could be better than real world by using color and highlighting. Also add color to the symbology.
Re 10:	Much better depth judgment with photo-realistic.
Re 11:	A little at DFW, but I think it would be of great value in the mountains.
Re 12:	Yes, but a line to the new runway would be a good addition too.
Re 13:	I vote for photo-realistic that is enhanced to display RNP and threats.
Re 14:	Generic is adequate and would be easier to keep up to date than photo-realistic. Need to highlight landing runway and have lead-in line to it.

Re 15:	Need color symbology and photo-realistic display on HUD.
Re 16:	Great! Since the HUD is closer to the eye, it gives bigger, wider FOV and makes flying easier.
Re 17:	The HUD is far better than any head-down displays for a number of reasons: (1) Wider FOV apparently, (2) head in natural position to land, (3) all instrumentation available in one spot.
Re 18:	Need color, need see-through capability when real world becomes visible.
Re 19:	Depth was harder to judge with monochrome display.
Re 20:	Somewhat better in areas of greater vertical terrain.
Re 21:	Generic has actually sharper images in some cases. Prominent landmarks stand out better.

Pilot 4 Comments

Re 1 Size-A:	The GS/LOC deviation indicators are somewhat small and more difficult to interpret than I would like. Anything greater than a 30° FOV makes the symbology and terrain info too difficult to interpret.
Re 2 Size-A:	I found the depth perception difficult due to the resolution of the terrain data, which seemed blurred and difficult to focus on. I had to continue to cross check the VSI, especially during the sidestep maneuver.
Re 3 Size-A:	30° FOV. For terminal area maneuvering, 30° FOV offered the best compromise between actual size (inside vs. outside) and terrain display for SA.
Re 4 Size-A:	Absolutely! I can envision the en route phase of flight being suited for the larger FOVs. This display of terrain would greatly enhance SA, especially when exercising events such as an emergency descent in mountainous terrain.
Re 5 Size-A:	Pilot Selectable! I found myself bouncing back between different FOVs. I think it would be a very subjective exercise to determine when the system should switch FOVs in a system with it engineered in.
Re 6 Size-A:	30°. See answer 10. 90° en route SA.
Re 7 Size-A:	Given the size limitation for retrofit a/c, this display is easy to interpret and is not obscured by the speed and/or altitude tape. During the sidestep maneuvers, I was able to pick up the new leading runway sooner than with the size-D display.
Re 8 Size-A:	Size.
Re 9 Size-A:	Better terrain resolution, larger GS/LC deviation indicators, and a vertical track error indicator for operations other than on final (absence of ILS).
Re 1 Size-D:	VSI indicator is too difficult to interpret. I like the pointer style. Sidestep maneuver is complicated by the tape outlines obscuring the runway.
Re 2 Size-D:	With all the flight parameters displayed on one instrument, workload is decreased and I found I was able to spend more time trying to evaluate the terrain. Resolution of terrain data still needs to be enhanced though.
Re 3 Size-D:	30°. See answer to 10.

Re 4 Size-D: See answer to 13.

Re 5 Size-D: See answer to 14.

Re 6 Size-D: Same as 15 except: I found myself switching between 30–45° FOV during the sidestep because the runway was obscured by the tapes during the maneuver.

Re 7 Size-D: Larger is better, easy interpretation of flight parameters. Easier to focus and decipher terrain objects. LOC/GS deviation indicators are easier to read.

Re 8 Size-D: Especially with the crosswind that we experienced, the runway can easily be obscured by the tapes, not only during the sidestep but also on straight-in final due to the crab angle!

Re 9 Size-D: Remove the borders on the tapes. Replace VSI trend arrow with pointer type. Better terrain resolution. Get rid of U FOV selection and replace it with 30°.

Re 1 Size-X: LOC/GS deviation scales can be increased in size. AS/ALT tapes seem to be too large.

Re 2 Size-X: The larger display makes it somewhat easier to decipher terrain data, but the smaller the FOV, the fuzzier/more blurry the image.

Re 3 Size-X: Same as 10, but with the larger display, I found it easier to tolerate the larger FOVs because they still presented terrain data that were readily identified.

Re 4 Size-X: Same as 13.

Re 5 Size-X: Same as 14.

Re 6 Size-X: 30°: Same as 16. 120°: Larger display allows enough resolution/clarity to interpret data.

Re 7 Size-X: Size. (1) Makes it easier to decipher objects and terrain, (2) allows more precise flying (except in RWC tunnel due to constant size box).

Re 8 Size-X: AS/ALT tape font too large. U FOV doesn't offer any capability.

Re 9 Size-X: Replace U with 30° FOV. Reduce font size on ALT/AS. Increase LOC/GS dev scale size.

Re 10: Photo-realistic offers much easier interpretation of depth perception. Generic terrain doesn't offer enough information (especially in a flat environment) to judge depth perception.

Re 11: Yes, especially if you're familiar with the airport that you're operating into. Knowing your environment is part of SA; therefore, having the detailed terrain data helps orientation.

Re 12: Same as 61; the PR terrain database allows those of us that supplement our navigational practices with local terrain/obstacles knowledge can use this to orient ourselves. In a black hole at night, every bit of orientation enhancement helps.

Re 13: None.

Re 14: Difficult to gain depth perception with generic. Doesn't offer any visual cues in flat terrain.

Re 15: Photo-realistic terrain data provides a comfort factor when the pilot can overlay terrain/objects on the real world. Allows much better depth perception.

Re 16:	Very easy, not difficult at all to "look thru" the display. Head up all the time is far superior to the head down concept.
Re 17:	The HUD resolution concept coupled with a certain amount of info on head-down display would be ideal (and expensive)! If I were to choose one or the other, HUD would prevail. The head-down display is so compelling that it invites the pilot to say down and would therefore require a safety pilot on all flights.
Re 18:	(1) Database should provide the pilot with objects that he can verify position with; (2) Allow pilot to "look thru" the terrain detail.
Re 19:	Photo: yes. Generic: None—over flat terrain, the HUD only shows a black hole.
Re 20:	Yes, see 61 and 62.
Re 21:	None except maybe less clutter.
Re 22:	See 73.

Pilot 5 Comments

Re 2 Size-A:	Situational Awareness = position in space (somewhat easy) + awareness of a/c state (checklists, config, avionics set p, pax announcements, etc.).
Re 3 Size-A:	60° FOV to stabilized final, then unity.
Re 4 Size-A:	FOV cannot have unity with size-A except for short final (symbology and terrain near/off bottom of display). Must use at least 60° in cruise/approach to see terrain.
Re 5 Size-A:	(1) Pilot selectable, (2) not thru touch screen, (3) no more than 3 or 4 discreet values.
Re 6 Size-A:	Unity (for all but size-A) gives best view of runway, most precise alignment, and best depth perception; 60° best combination when precise navigation and depth perception not important.
Re 7 Size-A:	(1) Retrofittable, (2) better SA in terrain-challenged airport, black hole approach, or IMC, (3) variable FOV, (4) color discrimination of symbology.
Re 8 Size-A:	(1) High inner loop workload, (2) can't couple, (3) loss of SA inside of aircraft (checklists, etc.), (4) difficult selection of FOV and scale factor, (5) loss of critical symbology in crosswind.
Re 9 Size-A:	(1) Bigger and side-by-side, (2) better human-factoring of symbology, layout, etc., (3) center symbology and FOV around flight-path vector, (4) make FOV and scale factor more easily selectable (using only right hand), (5) thicken lines on plan view map, (6) correct predictor "noodle" on plan view map, (7) separate control of brightness for symbology and terrain.
Re 2 Size-D:	See comments for size-A.
Re 3 Size-D:	60° for maneuvering. Unity for stabilized final.
Re 4 Size-D:	Depends on task: No tunnel—up and away—probably 90° (best horizon). Tunnel—up and away—60° (keeps symbology in close). Tunnel—stabilized final—unity.

Re 5 Size-D:	Pilot selectable—changing FOV changes pilot perception of altitude and groundspeed. Pilot needs to know exactly what FOV is in use and control when it changes.
Re 6 Size-D:	See question 16.
Re 7 Size-D:	(1) Bigger = better, (2) side-by-side is better, (3) terrain in photo mode is cleaner, (4) smaller FOVs easier to use, (5) better SA outside of a/c, especially in IMC, black hole, etc.
Re 8 Size-D:	(1) FOV and scale factor touch screen controls hard-to-use, (2) unable to couple = high workload, (3) loss of SA inside of a/c due to high inner loop workload, (4) loss of symbology in crosswind.
Re 9 Size-D:	(1) Replace touch screen with controls on pedestal, (2) human factor display symbology, (3) center symbology and FOV about flight-path predictor, (4) see question 19, (5) separate controls of brightness for symbology and terrain.
Re 2 Size-X:	Slightly lower workload due to larger display = slightly better SA inside the a/c.
Re 4 Size-X:	See question 32.
Re 5 Size-X:	Same as questions 14 and 33.
Re 6 Size-X:	See question 16.
Re 7 Size-X:	Same as question 36. X display is better than D, which is better than A, especially when using photo texturing.
Re 8 Size-X:	Same as question 37.
Re 9 Size-X:	Same as question 38.
Re 10:	Photo—only unity FOV, and then marginally. Generic—only unity FOV, and even more marginally.
Re 11:	No, except for airport features, such as runways. Would have to be very familiar with terrain features (interstates, buildings, etc.) to use other terrain features. Photo database had too many items in some FOVs—too easy to lose runway in other gray clutter, such as roads.
Re 12:	Type of terrain database didn't make much difference. Overall, the generic terrain was less busy and made runways stand out more.
Re 13:	(1) Less clutter, (2) better definition of airport/runway features, (3) faster update rate at high FOV; (4) easier to integrate EGPWS, (5) doesn't require airport-specific knowledge of terrain, (6) easier to make symbology stand out against background, (7) easier to keep updated.
Re 14:	(1) Less like "VFR", (2) could deprive crews with high familiarity with specific airports of some terrain cues.
Re 15:	Low resolution was not formally evaluated. Had it been, it would have been rated low because the terrain was too bright relative to the symbology. Generic was related higher than photo because the photo terrain had bright spots that obscured important symbology like the localizer scale and error bug.
Re 16:	The outside world was more visible through the generic texture than the photo texture. The low-resolution HUD completely obscured the outside world at normal brightness settings and had to be decluttered.

Re 17: HUD could stand alone if minor improvements were made, such as vertical speed tape. Combining with HDD display helps but is not necessary to achieve desired functionality.

Re 18: (1) Need to evaluate in black hole, IMC, and terrain; (2) need to provide obstruction to outside vision to simulate IMC; (3) need separate brightness controls for symbology and terrain.

Re 19: No, with either database. There was an overall sense of height relative to real terrain, but the height gamma and depth perception cues relative to the virtual terrain were very limited.

Re 20: Not here at DFW, where there are no significant terrain features. The only significant items are the airport and runway.

Re 21: (1) Less cluttered, (2) fewer bright spots that obscured symbology, (3) easier to update/maintain, (4) symbology easier to discriminate against background.

Re 22: Virtual runway did not overlay real runway, which caused initial confusion about where to place velocity vector. Problem for both databases.

Pilot 6 Comments

Re 1 Size-A: 6—symbols seemed small.

Re 3 Size-A: ≈30° FOV was best for flying the tunnels; ≈60° FOV was best for changing runways; ≈U-25° FOV was best for short final.

Re 4 Size-A: Terrain separation was not an issue at DFW. Using the synthetic vision to navigate was and doing so was very easy.

Re 5 Size-A: FOV should be pilot selectable. The wider FOVs (90–120) were not helpful in achieving the task at hand.

Re 6 Size-A: See question 10.

Re 7 Size-A: The display is very easy to use and gives me the cueing I need to fly an approach. The terrain makes it easy to orient myself with the runway.

Re 8 Size-A: U-FOV was difficult to use because of the limited size of the LOC and G/S indicators should be kept along the edge of the display. The size of the display requires the selection of many FOVs to get a good understanding of my situation. I used U, 30, 45, 55, and 60° FOV; each had its advantage. Larger FOVs 60°–120° were on smaller display; meant I needed to spend more time manipulating FOV to get the right perspective.

Re 9 Size-A: At higher FOV, the LOC/GS/Pitch symbols became compressed and unusable.

Re 1 Size-D: The display is designed to give the pilot better spatial awareness/SA, and it does a great job.

Re 3 Size-D: 30° was good for flying the tunnels. 50°–60° was good for changing the runways.

Re 4 Size-D: See question 10.

Re 5 Size-D: The FOV should be pilot selectable.

Re 6 Size-D: See question 10.

Re 7 Size-D: The larger display allowed for the selection of fewer FOVs. I didn't feel I needed as many different FOVs. More display space gave me more terrain with the right amount of detail to orient myself with. The larger display allowed for more detail to be displayed when changing runways and made it an easier task.

Re 8 Size-D: As the FOV got above 60°, the terrain became less realistic, but the higher FOVs could be used to verify traffic on a parallel approach. The higher FOVs, 90°–120°, caused the pitch scales, LOC and G/S, to compress and become unusable.

Re 1 Size-X: The larger display was easier to fly.

Re 2 Size-X: The larger display allowed more information to be displayed at smaller FOVs.

Re 3 Size-X: See question 10.

Re 4 Size-X: The size of the display allowed me to use fewer FOVs.

Re 5 Size-X: Even with more information being displayed, the FOVs should be pilot selectable.

Re 6 Size-X: See question 10.

Re 7 Size-X: See question 36. The larger display allowed me to spend less time switching FOVs.

Re 8 Size-X: See question 19.

Re 10: The photo-realistic database had the detail I use to line the aircraft up with the new runway during the runway changes. The level of detail helped determine rate of closure with objects over the ground and supplied cueing for runway centerline alignment.

Re 11: Yes. See question 60. The level of detail on approach and on the runway change maneuver gave me a better rate of closure cueing with objects over the ground.

Re 12: See question 60 and the objects along the runway centerline are aligned with the runway and allowed for easier alignment with the runway.

Re 13: The generic database might be better for operations other than approach and landing. I don't think the level of detail in the photo-realistic database is required for operation above 10,000 ft AGL.

Re 14: The generic database made it more difficult to change runways. The generic database could be improved for this task by projecting a runway centerline on the ground.

Re 15: The photo-realistic data gave better cueing.

Re 16: Excellent. It was necessary to turn the HUD image down to avoid obscuring objects on the ground.

Re 17: When I flew the HUD I tried to use only the HUD, and it worked great. Very little cross-checking with the head-down display was required.

Re 18: The photo-realistic data are best used on approach and help with rate of closure cueing.

Re 19:	Photo-realistic gave better rate of closure cueing.
Re 20:	Yes.
Re 22:	The HUD image was hard to control. It would be better if there were more controls over the values of brightness and contrast at the lower end of values. More shades of gray.

Appendix D

Tabular Listing of Quantitative Data

Table D1. Transition Data

[Data included in the table below correspond to the transition segment of the maneuver]

Subject	Display	Runway	Maxcut	Minfov	Maxfov	Meanfov	Minroll	Maxroll	Meanroll	Rollrms	Collrms	Whlrms	Rudrms
1	GA	17	25.6	30	30	30.00	-8.8	16.11	0.17	4.77	0.595	7.632	0.042
2	GA	35	26.8	12	45	43.63	-14.9	14.67	-0.39	6.90	0.666	9.822	0.013
3	GA	35	26.4	50	60	56.12	-19.1	20.11	-0.10	7.39	0.751	10.622	0.011
4	GA	35	40.0	30	40	34.68	-19.3	16.96	0.13	9.67	0.773	9.543	0.051
5	GA	17	36.9	60	60	60.00	-14.2	19.19	1.31	11.41	0.506	8.151	0.067
6	GA	17	34.5	30	60	49.69	-12.8	18.17	-0.02	9.16	0.653	12.046	0.015
1	GD	17	31.4	35	35	35.00	-10.3	16.20	0.31	5.55	0.693	5.836	0.045
2	GD	35	28.4	14.6	14.6	14.60	-18.6	19.49	-1.14	8.93	0.701	9.972	0.012
3	GD	35	29.4	40	40	40.00	-20.2	9.18	-0.68	8.33	0.496	7.710	0.005
4	GD	35	37.8	40	60	48.12	-21.5	16.23	0.03	10.79	0.795	9.689	0.051
5	GD	17	34.8	60	60	60.00	-18.0	16.66	0.80	10.28	0.521	7.921	0.067
6	GD	17	31.5	30	30	30.00	-22.2	16.37	0.15	7.82	0.582	11.508	0.007
1	GX	17	22.8	22.6	22.6	22.60	-6.8	15.26	0.08	4.33	0.716	9.310	0.047
2	GX	35	26.0	30	30	30.00	-16.6	20.92	-0.33	6.98	0.635	8.018	0.030
3	GX	35	21.7	25	25	25.00	-17.7	13.39	-0.68	6.56	0.573	8.120	0.009
4	GX	35	39.2	35	35	35.00	-19.7	26.74	0.29	12.04	0.959	10.546	0.053
5	GX	17	35.4	90	90	90.00	-13.3	17.04	1.43	9.85	0.617	7.860	0.067
6	GX	17	37.8	60	60	60.00	-17.2	20.12	0.00	11.02	0.633	12.395	0.022
1	HG	17	25.0	35	35	35.00	-6.0	18.06	-0.24	4.13	0.542	10.346	0.008
2	HG	35	27.0	60	60	60.00	-14.5	19.54	-0.22	6.66	0.745	9.211	0.038
3	HG	35	29.9	60	60	60.00	-18.2	17.44	0.10	7.78	0.511	7.594	0.050
4	HG	35	34.5	30	30	30.00	-17.7	12.91	-0.79	7.85	0.930	12.229	0.017
4	HG	35	34.3	30	30	30.00	-20.9	11.96	-0.49	7.66	1.051	12.743	0.017
5	HG	17	25.3	60	60	60.00	-4.4	15.30	1.08	5.95	0.537	6.102	0.062
6	HG	17	27.4	35	35	35.00	-12.1	19.42	0.58	6.68	0.443	9.405	0.028
1	HP	17	30.0	35	35	35.00	-6.4	18.62	-0.12	5.58	0.575	9.829	0.017
2	HP	35	35.0	60	60	60.00	-11.8	21.01	-0.90	8.67	0.595	10.563	0.022
3	HP	35	25.2	60	60	60.00	-13.7	7.15	-0.01	6.01	1.062	5.573	0.050
5	HP	17	29.9	60	60	60.00	-6.9	15.95	1.08	7.15	0.418	6.112	0.061
6	HP	17	23.4	35	35	35.00	-9.1	14.13	0.20	5.16	0.804	9.700	0.030
1	PA	17	25.5	25	25	25.00	-7.3	18.91	0.37	4.78	0.618	8.378	0.047
3	PA	35	21.9	35	35	35.00	-15.9	5.94	-0.46	5.00	1.010	6.358	0.010
4	PA	35	35.4	30	30	30.00	-20.1	16.70	0.09	10.46	0.648	10.153	0.050
5	PA	17	35.4	12	60	59.92	-14.6	15.17	1.18	8.92	0.455	8.652	0.070
6	PA	17	40.6	40	60	55.70	-14.5	19.61	0.33	10.99	0.615	9.583	0.003
1	PD	17	26.1	30	30	30.00	-6.2	16.60	0.46	4.48	0.650	5.951	0.047
2	PD	35	31.9	14.6	25	20.52	-15.9	14.03	-0.62	8.10	0.698	8.594	0.012
3	PD	35	23.2	35	35	35.00	-17.9	6.56	-0.48	6.18	0.309	7.093	0.002
4	PD	35	43.8	30	30	30.00	-23.7	15.03	-1.02	11.57	0.627	12.365	0.017
5	PD	17	28.4	14.6	90	25.90	-12.8	17.50	1.22	8.45	0.480	8.203	0.070
6	PD	17	37.4	60	60	60.00	-16.0	22.48	0.20	10.17	0.563	10.403	0.003
2	PX	35	30.7	22.6	22.6	22.60	-14.3	18.20	-0.63	8.58	0.572	8.018	0.011
3	PX	35	22.2	30	30	30.00	-18.3	9.45	-0.82	6.47	0.721	7.393	0.013
4	PX	35	39.9	30	30	30.00	-22.1	20.23	0.57	12.36	0.749	9.867	0.051
5	PX	17	37.2	60	60	60.00	-12.2	15.74	1.28	9.73	0.467	8.450	0.067
6	PX	17	32.2	22.6	45	39.69	-14.7	18.56	-0.07	8.18	0.482	13.695	0.023

Table D2. Tracking Data

[Data included in the table below correspond to the tracking segment of the maneuver]

Subject	Display	Resagl	Resxcg	Resorxcg	Locrms	Gsrms	Minfov	Maxfov	Meanfov	Collrms	Whlrms	Rudrms
1	GA	373.6	-5948	-10277	0.1	0.3	30	30	30.00	0.56	6.71	0.04
2	GA	1117.4	-17967	-16535	0.4	0.3	12	12	12.00	0.85	10.56	0.03
3	GA	386.5	-6487	-5056	0.4	0.3	50	50	50.00	0.62	10.56	0.01
4	GA	1159.4	-17688	-16256	0.2	0.4	30	30	30.00	0.72	8.93	0.05
5	GA	881.0	-13895	-18225	0.1	0.5	12	60	15.36	0.52	5.72	0.07
6	GA	848.6	-14454	-18783	0.3	0.4	30	30	30.00	0.42	11.45	0.02
1	GD	667.9	-10450	-14780	0.2	0.7	35	35	35.00	1.03	3.20	0.04
2	GD	1141.5	-19964	-18532	0.2	0.3	14.6	14.6	14.60	0.77	12.13	0.03
3	GD	1117.0	-17967	-16536	0.1	0.2	40	40	40.00	0.38	6.35	0.02
4	GD	1253.1	-19485	-18053	0.1	0.3	40	40	40.00	0.74	8.97	0.05
5	GD	840.1	-12963	-17293	0.2	0.7	14.6	60	16.96	0.40	7.95	0.07
6	GD	615.5	-10652	-14982	0.1	0.4	14.6	30	24.29	0.55	11.52	0.01
1	GX	361.4	-6548	-10878	0.4	0.2	22.6	22.6	22.60	0.73	7.46	0.05
2	GX	819.8	-14243	-12812	0.5	0.2	30	30	30.00	0.38	8.53	0.03
3	GX	903.8	-14841	-13409	0.2	0.4	25	25	25.00	0.48	7.14	0.02
4	GX	1343.9	-20552	-19121	0.4	0.6	35	35	35.00	0.89	9.54	0.05
5	GX	763.6	-13533	-17863	0.3	0.2	22.6	90	29.57	0.43	7.76	0.07
6	GX	924.5	-15774	-20104	0.2	0.2	22.6	60	44.02	0.41	12.32	0.02
1	HG	494.5	-7781	-12111	0.2	0.4	35	35	35.00	0.82	10.21	0.01
2	HG	1041.4	-16377	-14946	0.0	0.3	60	60	60.00	0.59	9.19	0.02
3	HG	942.8	-15361	-13930	0.2	0.5	60	60	60.00	0.45	4.86	0.05
4	HG	892.8	-15916	-14485	0.1	0.2	30	30	30.00	0.90	12.41	0.02
4	HG	772.1	-12966	-11535	0.2	0.1	30	30	30.00	1.05	13.69	0.02
5	HG	503.9	-7761	-12090	0.2	0.5	60	60	60.00	0.36	4.74	0.06
6	HG	583.8	-9245	-13575	0.0	0.1	35	35	35.00	0.34	7.21	0.03
1	HP	646.3	-9426	-13755	0.2	0.8	35	35	35.00	0.79	8.70	0.03
2	HP	1155.4	-19967	-18536	0.3	0.2	60	60	60.00	0.51	10.38	0.04
3	HP	848.8	-15856	-14424	0.1	0.6	60	60	60.00	0.96	3.65	0.05
5	HP	612.8	-10115	-14445	0.1	0.3	60	60	60.00	0.27	6.51	0.06
6	HP	561.4	-9192	-13522	0.1	0.2	35	35	35.00	0.69	9.48	0.03
1	PA	576.8	-8435	-12764	0.6	0.7	25	25	25.00	0.88	6.18	0.05
3	PA	755.9	-11747	-10316	0.2	1.3	35	35	35.00	0.94	6.90	0.02
4	PA	1202.1	-19271	-17839	0.3	0.2	30	30	30.00	0.70	7.79	0.05
5	PA	814.4	-14332	-18662	0.1	0.3	12	25	19.71	0.34	9.50	0.07
6	PA	939.0	-15495	-19825	0.3	0.4	12	90	40.30	0.51	8.29	0.01
1	PD	586.9	-10072	-14402	0.2	0.4	30	30	30.00	1.05	5.95	0.05
2	PD	1156.9	-19810	-18379	0.1	0.3	14.6	25	14.79	0.52	10.58	0.02
3	PD	902.5	-15240	-13809	0.4	0.1	35	35	35.00	0.27	7.12	0.01
4	PD	1250.9	-20641	-19209	0.1	1.2	30	30	30.00	0.62	11.66	0.02
5	PD	694.5	-12137	-16467	0.8	0.5	14.6	90	21.37	0.43	10.27	0.07
6	PD	914.1	-14211	-18541	0.3	0.6	14.6	60	27.44	0.51	11.90	0.01
2	PX	1208.6	-20157	-18726	0.2	0.2	22.6	22.6	22.60	0.52	10.65	0.03
3	PX	833.0	-14528	-13096	0.2	0.3	30	30	30.00	0.71	7.25	0.01
4	PX	1336.4	-20799	-19368	0.2	0.5	30	30	30.00	0.68	8.44	0.05
5	PX	758.4	-13275	-17605	0.4	0.2	22.6	60	25.56	0.33	6.67	0.06
6	PX	552.4	-9526	-13855	0.6	0.4	22.6	22.6	22.60	0.54	12.83	0.02

REPORT DOCUMENTATION PAGE	*Form Approved OMB No. 0704-0188*

1. REPORT DATE *(DD-MM-YYYY)*	2. REPORT TYPE	3. DATES COVERED *(From - To)*
01- 05 - 2003	Technical Publication	

4. TITLE AND SUBTITLE	5a. CONTRACT NUMBER
Flight Test Comparison of Synthetic Vision Display Concepts at Dallas/Fort Worth International Airport	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	**5d. PROJECT NUMBER**
Glaab, Louis J.; Kramer, Lynda J.; Arthur, Trey; Parrish, Russell V.; and Barry, John S.	**5e. TASK NUMBER**
	5f. WORK UNIT NUMBER 728-60-10-01

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)	8. PERFORMING ORGANIZATION REPORT NUMBER
NASA Langley Research Center Hampton, VA 23681-2199	L-18278
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	**10. SPONSOR/MONITOR'S ACRONYM(S)**
National Aeronautics and Space Administration Washington, DC 20546-0001	NASA
	11. SPONSOR/MONITOR'S REPORT NUMBER(S) NASA/TP-2003-212177

12. DISTRIBUTION/AVAILABILITY STATEMENT
Unclassified - Unlimited
Subject Category 03
Availability: NASA CASI (301) 621-0390 Distribution: Standard

13. SUPPLEMENTARY NOTES
Glaab, Kramer, Arthur, and Russell: Langley Research Center. Barry: Lockheed Martin.
An electronic version can be found at http://techreports.larc.nasa.gov/ltrs/ or http://techreports.larc.nasa.gov/cgi-bin/NTRS

14. ABSTRACT
Limited visibility is the single most critical factor affecting the safety and capacity of worldwide aviation operations. SVS technology can solve this *visibility* problem with a *visibility* solution. These displays employ computer-generated terrain imagery to present 3D, perspective out-the-window scenes with sufficient information and realism to enable operations equivalent to those of a bright, clear day, regardless of weather conditions. To introduce SVS display technology into as many existing aircraft as possible, a retrofit approach was defined that employs existing HDD display capabilities for glass cockpits and HUD capabilities for the other aircraft. This retrofit approach was evaluated for typical nighttime airline operations at a major international airport. Overall, 6 evaluation pilots performed 75 research approaches, accumulating 18 hours flight time evaluating SVS display concepts that used the NASA LaRC's Boeing B-757-200 aircraft at Dallas/Fort Worth International Airport. Results from this flight test establish the SVS retrofit concept, regardless of display size, as viable for tested conditions. Future assessments need to extend evaluation of the approach to operations in an appropriate, terrain-challenged environment with daytime test conditions.

15. SUBJECT TERMS
Synthetic vision systems; Flight testing; Advanced displays

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			STI Help Desk (email: help@sti.nasa.gov)
					19b. TELEPHONE NUMBER *(Include area code)*
U	U	U	UU	143	(301) 621-0390

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std. Z39.18