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Flight Test Evaluation of Synthetic Vision Concepts at a Terrain Challenged Airport

Lynda J. Kramer, Lawrence J. Prinzel III, Randall E. Bailey, Jarvis J. Arthur III, and Russell V. Parrish
Langley Research Center, Hampton, Virginia

February 2004

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National Aeronautics and
Space Administration

Langley Research Center
Hampton, Virginia 23681-2199

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Symbols & Abbreviations

AFL	Above Field Level
AGL	Above Ground Level
ANOVA	Analysis of Variance
ANP	Actual Navigation Performance
ARIES	Airborne Research Integrated Experiment System
ASIST	Aviation Safety Investment Strategy Team
ATL	FAA airport identifier for The William B. Hartsfield Atlanta International Airport
AVL	FAA airport identifier for Asheville Regional Airport
AvSP	Aviation Safety Program
CFIT	Controlled Flight Into Terrain
CNS/ATM	Communication Navigation Surveillance/Air Traffic Management
COS	FAA airport identifier for Colorado Springs, Colorado Airport
DEM	Digital Elevation Model
DFW	FAA airport identifier for Dallas/Fort Worth International Airport
DIME	Database Integrity Monitoring Equipment
DME	Distance Measuring Equipment
DTW	FAA airport identifier for Detroit Metropolitan Wayne County Airport
EADI	Electronic Attitude Direction Indicator
EFIS	Electronic Flight Instrumentation System
EGE	FAA airport identifier for Eagle County, Colorado Regional Airport
EGPWS	Enhanced Ground Proximity Warning System
EP	Evaluation Pilot
EVS	Enhanced Vision System
EWR	FAA airport identifier for Newark Liberty International Airport
FAA	Federal Aviation Administration
FANS	Future Air Navigation System
FDRS	Flight Deck Research System
FLIR	Forward-Looking Infra-Red
FMS	Flight Management System
FOV	Field of View
FSIL	Flight Systems Integration Laboratory
FTE	Flight Technical Error
GEOTIFF	Georeferenced Tagged Image File Format
GPS	Global Positioning System
GPWS	Ground Proximity Warning System
HDD	Head-Down Display
HGS	Head-Up Guidance System
HUD	Head-Up Display
Hz	Hertz
ICAO	International Civil Aviation Organization
IFD	Integration Flight Deck
ILS	Instrument Landing Systems
IMC	Instrument Meteorological Conditions
in	inches
JFK	FAA airport identifier for John F. Kennedy International Airport
LaRC	Langley Research Center
LAX	FAA airport identifier for Los Angeles International Airport

LDA	Localizer-DME Approach
LGA	FAA airport identifier for La Guardia Airport
MASPS	Minimum Aviation System Performance Standards
MSL	Mean Sea Level
MSP	FAA airport identifier for Minneapolis-St Paul International Airport
n	number of samples
NASA	National Aeronautics and Space Administration
ND	Navigation Display
NED	National Elevation Dataset
nmi	nautical mile
ORD	FAA airport identifier for Chicago O'Hare International Airport
PFD	Primary Flight Display
RIPS	Runway Incursion Prevention System
RMS	Root Mean Square
RNAV	RNP Area Navigation
RNP	Required Navigation Performance
SA	Situation Awareness
SA-SWORD	Situational Awareness – Subjective Workload Dominance
SEA	FAA airport identifier for Seattle-Tacoma International Airport
SNK	Student-Newman-Keuls
SP	Safety Pilot
SV	Synthetic Vision
SVDC	Synthetic Vision Display Concepts
SVS	Synthetic Vision Systems
SVS-GE	Synthetic Vision Systems – Graphics Engine
SVS-RD	Synthetic Vision Systems – Research Display
SXGA	Super-eXtended Graphics Array (1280 by 1024 pixels)
TAWS	Terrain Awareness and Warning System
TOGA	Takeoff/Go-around
USGS	United States Geological Survey
UTM	Universal Transverse Mercator
VISTAS	Visual Imaging Simulator for Transport Aircraft Systems
VMC	Visual Meteorological Conditions
VNAV	Vertical navigation
VOR	Very high frequency Omni-direction Radio
VRD	Vision Restriction Device
XGA	eXtended Graphics Array (1024 by 768 pixels)

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Executive Summary

Limited visibility is the single most critical factor affecting both the safety and capacity of worldwide aviation operations. In commercial aviation alone, over 30-percent of all fatal accidents worldwide are categorized as controlled flight into terrain (CFIT), where a mechanically sound and normally functioning airplane is inadvertently flown into the ground, water, or an obstacle, principally due to the lack of outside visual reference and situation awareness. The National Aeronautics and Space Administration (NASA) Aviation Safety Program's Synthetic Vision Systems (SVS) Project is developing technologies with practical applications that will mitigate low visibility conditions as a causal factor to civil aircraft accidents, as well as replicate the operational benefits of flight operations in unlimited ceiling and visibility day conditions, regardless of the actual outside weather or lighting condition. The technologies will emphasize the cost-effective use of synthetic/enhanced-vision displays; worldwide navigation, terrain, obstruction, and airport databases; and Global Positioning System (GPS)-derived navigation to mitigate "visibility-induced" (lack of visibility) errors for all aircraft categories. A major thrust of the SVS Project is to develop and demonstrate affordable, certifiable display configurations which provide intuitive out-the-window terrain and obstacle information, including guidance information for precision navigation and obstacle/obstruction avoidance for commercial and business aircraft.

To date, much of the SVS research has focused on introducing SVS display technology into as many existing aircraft as possible by providing a retrofit approach. 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. A major NASA flight test at Dallas/Fort Worth (DFW) airport and several simulator studies have occurred for assessment and evaluation of the SVS developments and the retrofit approach. The HDD objective of these studies was to examine whether an SVS display could be retrofitted into an Electronic Flight Instrumentation System (EFIS) Size "A" (5.25 in. wide by 5 in. tall) (e.g., B-757-200) Electronic Attitude Direction Indicator (EADI) and Size "D" (6.4 in. wide by 6.4 in. tall) (e.g., B-777) Primary Flight Display (PFD). A Size "X" (9 in. wide by 8 in. tall) head-down display was also tested that may represent the display real estate available on future aircraft. The HUD objective was to examine the feasibility of the concept of retrofitting SVS display technology with HUDs for aircraft without raster-capable HDDs. The feasibility of the concept of retrofitting SVS display technology with HUDs was verified for nighttime operations. Two terrain-texturing techniques were also evaluated during the research. One method of terrain texturing, generic texturing, involved the selection of terrain color based on absolute altitude. The other method of terrain texturing, photo-realistic texturing, employed full-color ortho-rectified aerial photographs draped over the elevation model. The results of those studies confirmed that an SVS display, with pilot-selectable field of view (FOV), could be incorporated as part of an EFIS suite and effectively replace an EADI or PFD. Regardless of HDD display size, and for the nighttime HUD application, pilots reported greater situation awareness and had lower flight technical error (FTE) while operating with the SVS displays compared to conventional displays. For both HDD and HUD applications, no significant performance effects were found between texturing techniques, although most of the pilots preferred the photo-realistic terrain texturing technique to the generic texturing technique.

The results of previous research have documented the unquestionable promise of SVS to enhance situation awareness and improve aviation safety during approaches to terrain and operationally-complex airports. The DFW flight test showed that all SVS display concepts provided precise path control and significantly improved spatial awareness for approaches to the DFW airport under nighttime conditions. Although the fixed-based simulator results had provided convincing data on the efficacy of SVS for terrain-challenged environments, these results had yet to be replicated and validated under operational conditions like that conducted at DFW in 2000. In 1999, a flight test / demonstration was conducted

using the SVS technology to make approaches to the Asheville, North Carolina (AVL) airport, but no empirical data was collected to substantiate the claims that SVS was effective in terrain-challenged environments. Therefore, the Aviation Safety program and SVS Project conducted research flight operations at Eagle-Vail, CO (EGE) to further examine the utility, capabilities, and potential of SVS to enhance situation awareness and improve pilot performance for complex approaches in mountainous environments.

The flight test was conducted to evaluate three SVS display types (Head-up Display, Head-Down Size A; Head-Down Size X) and two terrain texture methods (photo-realistic, generic) in comparison to the simulated Baseline Boeing-757 Electronic Attitude Direction Indicator and Navigation / Terrain Awareness and Warning System displays. These independent variables were evaluated for path error, situation awareness, and workload while making approaches to Runway 25 and 07 and during simulated engine-out Cottonwood 2 and KREMM departures. The results of the experiment showed significantly improved performance, situation awareness, and workload for SVS concepts compared to the Baseline displays and confirmed the retrofit capability of the Head-Up Display and Size A SVS concepts. The research also demonstrated that the tunnel guidance display concept used within the SVS concepts achieved required navigation performance (RNP) criteria. These findings are a strong verification of the SVS retrofit approach. That is, HUD or HDDs of any size or texture method tested were an equally effective means of implementing SVS concepts to achieve FTE and RNP benefits. The top-level results of the EGE flight test concerning the improved path performance, enhanced situation awareness, and lower associated workload 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.

This paper documents the EGE flight test experiment and presents suggestions for research thrusts for further development of future embodiments of synthetic vision systems.

Introduction

The Synthetic Vision Systems (SVS) element of the National Aeronautics and Space Administration's (NASA) Aviation Safety Program (AvSP) is striving to eliminate poor visibility as a causal factor in aircraft accidents as well as enhance operational capabilities of all aircraft. To accomplish these safety and situation awareness (SA) improvements, the SVS concept is designed to provide the pilot an unobstructed view of the world around the aircraft through the display of computer-generated imagery derived from an onboard database of terrain, obstacle, and airport information. To accomplish the operational enhancements, the SVS concept includes the intuitive display of intended flight path by tunnel or pathway-in-the-sky presentations. When coupled with a synthetic or enhanced view of the outside world, the spatially-integrated depiction of the intended aircraft flight path and its relation to the world provides an intuitive, easily interpretable display of flight-critical information for the pilot.

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. Since the beginning of flight, the aviation industry has continuously developed various devices to overcome low-visibility issues, such as attitude indicators, radio navigation, and instrument landing systems. Recent advances include moving map displays, incorporating advances in navigational accuracies from the Global Positioning System (GPS), and Terrain Awareness and Warning Systems (TAWS), such as Honeywell's Enhanced Ground Proximity Warning System (EGPWS). All of the aircraft information display concepts developed to date, however, require the pilot to perform various additional levels of mental model development, maintenance, and information decoding in a real-time environment when outside visibility is restricted (e.g., Theunissen, 1997).

Better pilot SA during low visibility conditions is potentially offered by SVS displays because of the natural cues provided by a three-dimensional perspective display of the outside world showing unlimited ceiling and visibility conditions. New technological developments in navigation performance, low-cost attitude and heading reference systems, computational capabilities, and display hardware allow for the prospect of SVS displays for virtually all aircraft classes. SVS display concepts employ computer-generated terrain imagery, on-board databases, and precise position and navigational accuracy to create a three dimensional perspective presentation of the outside world, with necessary and sufficient information and realism, to enable operations equivalent to those of unlimited ceiling and visibility conditions regardless of the actual outside weather. The safety outcome of SVS is a display that should help reduce, or even prevent, controlled flight into terrain (CFIT), which is the single greatest contributing factor to fatal worldwide airline and general aviation accidents (Boeing, 1998). Other safety benefits include reduced runway incursions and loss-of-control accidents (Williams et al., 2001). Operational benefits potentially include more approach and departure options and lower visibility minimums for SVS equipped aircraft. For a more detailed description of the SVS project, please see Appendix A.

Safety Benefits of SVS

It is highly unlikely that conventional display concepts can significantly increase safety as new functionality and new technology cannot simply be layered onto previous design concepts since the current system complexities are already too high (Theunissen, 1997). Better human-machine interfaces require a fundamentally new approach. One such approach applies the fundamental advantage of perspective flight path displays relative to conventional displays. 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 can now provide information about the margins within which the pilot is allowed to operate. These displays are augmented to show such information as spatial constraints and terrain constraints, rather than just showing conventional flight director commands, which only indicate an error, seemingly independent of the actual constraints. These additional display elements provide guidance that does not force the pilot to apply a continuous compensatory control strategy. Only in this way can human flexibility be exploited. This is a fundamental difference between current and SVS displays – that synthetic vision embodies the concept of "human-centered" design by providing natural versus coded information to the pilot (Theunissen, 1997). Appendix B describes the concept of human-centered design and the theoretical foundations for synthetic vision.

Because SVS displays are posited to provide both natural and coded information to the pilot, better pilot spatial situation awareness during low visibility conditions can be achieved. Synthetic vision technology will allow the issues associated with limited visibility to be solved with a vision-based solution, making every flight the equivalent of a clear daylight operation, which will help improve situation awareness, lower workload, and support proper development of pilots' mental models (see Appendix C). Therefore, SVS can have a most significant impact on improving aviation safety, as limited visibility has often been cited as the single greatest contributing factor in fatal worldwide airline and general aviation accidents (Boeing, 1996).

Consider that one of the major classifications of aviation accidents involving visibility issues is CFIT and that CFIT is the greatest cause of aviation fatalities. A CFIT accident is defined as "one in which an otherwise-serviceable aircraft, under control of the crew, is flown (unintentionally) into terrain, obstacles or water, with no prior awareness on the part of the crew of the impending collision" (Wiener, 1977). Enders, et al., (1996) noted that worldwide, the chances of CFIT accidents are 5 times higher in non-precision approaches. SVS could have a significant impact in ameliorating the incidence of this accident category (Arthur et al., 2003). For commercial transport aircraft, instant recognition and correction of visibility-induced errors may eliminate CFIT. If accurate positioning information of other traffic were incorporated into the system, SVS could also help to eliminate runway incursions. For general aviation aircraft, a lower cost implementation of such a system could help to prevent visibility-induced loss-of-control accidents by providing an intuitive, easy-to-fly visual reference for Visual Meteorological Conditions (VMC)-like operations in Instrument Meteorological Conditions (IMC). It would also be anticipated that SVS technology could serve to increase national airspace system capacity by providing the potential for VMC-like operations more of the time (Hemm, 2000; Hemm, Lee, Stouffer, & Gardner, 2001).

Operational Benefits of SVS

Aside from the safety benefits accrued from the increased SA with reduced workload provided by the natural information presentation of synthetic vision displays, considerable operational benefits are also potentially available through provisions for flight operations in IMC resembling those conducted in VMC. These potential benefits could include lower landing minimums, more approach and departure options, more complex path structures to avoid hazardous or restricted (noise, security) areas, reduced training time, etc. Among these, a significant operational benefit of SVS would include helping to meet new Federal Aviation Administration (FAA) required navigation performance (RNP) criteria.

RNP is a statement of the navigation performance accuracy necessary for operation within a defined airspace. RNP airspace is a generic term referring to airspace, routes, and legs, where minimum navigation performance requirements have been established and aircraft must meet or exceed that performance to fly in that airspace. The system performance requirements for RNP Area Navigation (RNAV) is that each aircraft operating in RNP airspace shall have total horizontal system error components in the cross-track and along-track directions that are less than the RNP value 95% of the flying time. Vertical navigation (VNAV) capability further enhances flight operations by enabling the specification of a flight path vertically for the lateral flight path. The system performance requirements for VNAV are that for at least 99.7% of the time the navigational performance in the vertical plane, or the total vertical system error, is less than a specified altitude deviation measure based on the airspace being flown in (below 5000 feet mean sea level (MSL), 5000-10000 feet MSL, above 10000 feet MSL) and the type of flight operation (level flight/climb/descent or flight along specified vertical profile) being performed (see table 1). For more information about RNP, please see Appendix D.

Table 1. Vertical Accuracy Performance Requirements

Error Source	Level Flight Segments and Climb/Descent Intercept of Clearance Altitudes (MSL)			Approach along Specified Vertical Profile (MSL)		
	At or Below 5000 ft	5000 ft to 10000 ft	Above 10000 ft	At or Below 5000 ft	5000 ft to 10000 ft	Above 10000 ft
Altimetry	90 ft	200 ft	250 ft	140 ft	265 ft	350 ft
RNAV Equipment	50 ft	50 ft	50 ft	100 ft	150 ft	220 ft
Flight Technical	150 ft	240 ft	240 ft	200 ft	300 ft	300 ft
Total Root-Sum-Square (RSS)	190 ft	320 ft	350 ft	265 ft	430 ft	510 ft

RNP defines that an aircraft's actual navigation performance will be required to meet certain navigation precision criteria. Synthetic Vision is postulated to contribute significantly to achieving RNP through the use of pathway displays and guidance symbology. Research has shown that the use of pathway displays and predictive guidance can significantly reduce flight technical error (e.g., Haskell & Wickens, 1993; Wickens & Prevett, 1995; Theunissen, 1997). Therefore, SVS may not only increase aviation safety but may also have significant operational benefits that, in turn, can result in substantial economic benefits.

Economic Benefits of SVS

Hemm (2000) and Hemm et al. (2001) did a benefit estimation of SVS technologies and concluded that synthetic vision has significant potential not only for improving aviation safety and increasing navigation precision but can also provide for other considerable economic benefits. The analyses were based on the assumptions that SVS could reduce runway occupancy time in low visibility; reduce departure minimums; reduce arrival minimums; better allow for converging and circling approaches, especially for dual and triple runway configurations; reduce inter-arrival separations; and provide for independent operations on closely-spaced parallel runways. A cost-benefit analysis, based on those assumptions at 10 airports (DFW, ORD, LAX, ATL, DTW, MSP, EWR, SEA, LGA, JFK), calculated the average cost savings to airlines for the years 2006 to 2015 to be $2.25 billion. Part of the rationale for the AvSP SVS Project choosing Dallas/Fort Worth (DFW) (Glaab et al., 2003) and Eagle County, Colorado Regional (EGE) airport (Kramer et al., 2003) locations to conduct flight test research was to demonstrate that SVS could allow operations into runways (i.e., EGE Runway 07) that normally are not used, especially in IMC.

Challenges to Synthetic Vision

Although there is significant potential for SVS to help meet national aviation goals, there are still considerable research challenges that need to be addressed. To identify these challenges, a workshop resulting in a concept of operations for commercial and business aircraft was held in early 2000 (Williams, et al., 2001). A similar workshop was hosted that focused on general aviation aircraft. The focus of these events was to obtain wide ranging input on the benefits and features which synthetic vision might incorporate. This meeting included representatives from NASA, Department of Defense, FAA, industry, professional organizations, airlines, aircraft and avionics manufacturers, airports, and academic institutions. The result of the workshop was a "shopping list" of research issues that need to be explored in developing SVS display concepts. Primary among them, expressed as questions, are:

- How can an SVS display be retrofitted into an aircraft class that has limited real-estate display space?

- What are the perceptual issues involved with minification and increased field of views on smaller SVS displays?

- What is the best way to present synthetic terrain and symbology to enhance situation awareness?

- Can an SVS display improve SA and reduce workload?

- What are the cognitive issues that may affect safety of flight when pilots fly a "compelling" synthetic vision scene?

- What is the best way to display the synthetic vision scene and what are the database and sensor requirements to ensure the integrity of a synthetic vision system?

The NASA SVS-Commercial and Business aircraft element is using these issues as guidance in its research plans and a significant amount of research has been conducted, as discussed in the next section.

NASA SVS Human Factors Research

NASA SVS Simulator Research Experiments. An important issue for the SVS concept is whether useful and effective SVS displays can be implemented on limited size display spaces as would be required to implement this technology on older aircraft with physically smaller instrument spaces. With computer generated 3-dimensional imagery, SVS display concepts can provide pilot-selectable display Field of View (FOV) control to enhance display effectiveness, potentially overcoming size constraint limitations. Comstock, et al., (2001) conducted a study to examine how approaches using SVS on smaller display sizes affect performance and situation awareness. In this study, prototype SVS displays were shown on the following display sizes: (a) ARINC Size A (e.g., 757 Electronic Attitude Direction Indicator), (b) ARINC Size D (e.g., 777 Primary Flight Display), and (c) new size "X" (Rectangular flat-panel, approximately 20 x 25 cm). Testing was conducted in the Visual Imaging Simulator for Transport Aircraft Systems (VISTAS)-I, which is a high-resolution graphics workstation at NASA Langley Research Center. Specific issues under test included the display size and the FOV to be shown on the display and, directly related to FOV, the degree of minification of the displayed image or picture. Using simulated approaches to Asheville, NC airport runways (FAA identifier, AVL), no significant lateral or vertical performance differences were found for any display size or FOV condition. Preferred FOV based on performance was determined by using approaches during which pilots could select FOV. Mean preference ratings for FOV were in the following order: (1) 30°, (2) Unity, (3) 60°, and (4) 90°, and held true for all display sizes tested.

A second study by Stark, et al., (2001) was conducted to further explore issues of display size, FOV, and tunnel guidance on pilot performance and SA. Tunnel guidance was expected to improve pilot performance, increase SA, and decrease workload. Results of the study supported these hypotheses. Both horizontal and vertical path error were indeed reduced by tunnel guidance. Pilots were able to stay on path more accurately with the assistance of the tunnel, and these findings support previous pathway research (see Doherty & Wickens, 2001 for a review). Pilots also verbally reported "feeling" like they were better able to stay on path when using the tunnel guidance system, and these feelings were accompanied by a statistically significant reduction in mental workload measurements. One pilot commented that he was so "in tune" with the guidance system that it was almost "too easy" to fly. The "intuitiveness" of the tunnel concept contributed to significantly higher situation awareness ratings for the synthetic vision concepts.

Dallas Fort-Worth Flight Test. To introduce SVS display technology into as many existing aircraft as possible, a retrofit approach was postulated. 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. This retrofit approach takes advantage of the growing numbers of HUDs being fitted into the commercial fleet due to HUD operational benefits.

Previous research in a fixed-based simulator at NASA Langley Research Center (LaRC) (Comstock et al., 2001) indicated that an SVS display could significantly enhance SA in both an operationally challenging environment (multiple runways and taxiways at DFW) and a terrain-challenged environment (at AVL). The SVS retrofit approach was evaluated and initially validated for typical nighttime airline operations at DFW International Airport in September 2000. 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. The SVS HDD concepts evaluated included variations in display size, with pilot-selectable FOV, and in methods of terrain texturing. SVS HUD concept evaluations also included variations in the method of terrain texturing. Two types of terrain texturing were employed: photo-realistic texturing and elevation-based color-coded texturing (also referred to as generic texturing).

Results (Glaab et al., 2003) 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. All pilots acknowledged the enhanced situation awareness provided by all of the SVS (HDD and HUD) concepts. Regardless of display size, pilots selected HDD FOVs of approximately 50 degrees, or higher, during initial approach segments, such as on downwind and base legs, and consistently reduced the selected FOV to approximately 30 degrees, or less, for low final approach segments. Display size, selected FOV, and minification are correlated. Therefore, the selected FOV/phase-of-flight result above can be expressed in another way - as range to touchdown decreased, the minification factor moved toward unity (i.e., no minification). Also, pilots selected smaller minification factors for the larger-sized HDDs regardless of phase-of-flight (as display size increased, the minification factor moved toward unity). With these results, pilot-selectable display FOV control became the accepted standard approach to overcome display size constraint limitations associated with HDDs within the NASA SVS Project.

The majority of the pilots participating in the DFW tests preferred the photo-realistic terrain texturing technique to 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 by results demonstrating effective SVS presentation on this type of display device. Pilots also commented that presentation of SVS imagery on the HUD (with a minification factor of unity - i.e., no minification) was not only acceptable, but actually preferred, over the HDDs. The top-level results of the 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 established the SVS retrofit concept approach as viable, at least in the benign terrain environment of DFW in nighttime operations.

Current Study

The results of previous research have documented the unquestionable promise of SVS to enhance situation awareness and improve aviation safety during approaches to terrain- (e.g., 1999 AVL demonstration; Comstock et al., 2001; Stark et al., 2001) and operationally-complex (e.g., 2000 DFW flight test) airports. The DFW flight test showed that all SVS display concepts provided precise path control and significantly improved spatial awareness for approaches to the DFW airport under nighttime conditions. However, although the fixed-based simulator results had provided convincing data on the efficacy of SVS for terrain-challenged environments, these results had yet to be replicated and validated under operational conditions like that conducted at DFW in 2000. In 1999, a flight test / demonstration was conducted using the SVS technology to make approaches to AVL airport, but no empirical data was collected to substantiate the claims that SVS was effective in terrain-challenged environments. Therefore, the Aviation Safety Program and SVS Project conducted research flight operations at Vail, CO to further examine the utility, capabilities, and potential of SVS to enhance situation awareness and improve pilot performance for complex approaches in mountainous environments. This paper documents that flight test experiment.

Goals and Objectives

The goal of the flight test conducted at EGE was to extend the assessment of the SVS retrofit approach to operations in a terrain-challenged operational environment with testing in daytime conditions. EGE represented an ideal location to test the effectiveness of SVS technologies for terrain awareness and separation for approaches and departures that put the aircraft close to mountainous terrain.

SVS Display Concepts

Six NASA SVS tactical display configurations were evaluated. These configurations were obtained by presenting SVS terrain databases of two terrain texturing types (generic or photo-realistic) on three displays: a HUD and two HDD sizes (A or X).

Terrain Texturing Types. Terrain-texturing refers to the method used to fill the polygons that comprise the rendered terrain database. The two texturing concepts tested were elevation-based color-coding, or generic, and photo-realistic. The generic texturing concept consisted of applying equal-height coloring bands that correspond to different absolute terrain elevation levels, similar to the colors employed for Visual Flight Rules sectional charts. Lower terrain levels were colored with darker colors, while higher terrain levels were assigned lighter colors. A certain shade of green was set to the field elevation. The photo-realistic texturing was derived from full color ortho-rectified aerial photographs. The resulting scene was a highly realistic view due to the photographic imagery employed.

HUD Concept. As mentioned previously, the NASA SVS Project is investigating the potential of HUD technology as a retrofit solution for display of terrain database SVS concepts in non-glass cockpits. As such, the HUD is used in a manner not traditionally employed in commercial aircraft operations. The SVS terrain database scene is presented on the HUD as a raster image with stroke symbology overlaid upon it. This concept for a SVS-HUD 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. (The FAA has just recently certified an infrared EVS for use on a business aircraft.) In the SVS-HUD concept, the terrain database scene is displayed instead of the sensor EVS image. Unlike EVS displays, the SVS-HUD concept maintains a “clear sky” so there is no obstruction of that area of the display. (This is in contrast to an EVS image which displays a sensor image of the sky.) Below the horizon, the terrain raster image can obstruct the view of the outside real world, just as an EVS display can, particularly if the raster brightness is not appropriately controlled by the pilot. Obstruction of the outside real world scene by such a display is a recognized certification issue and a rapid means of decluttering the SVS imagery from the HUD was provided to the evaluation pilot. In addition to the raster, nominal flight information symbology characteristic of most airline HUDs was overlaid on the HUD imagery.

HDD Tactical Display Sizes. Two different SVS-HDD configurations were evaluated during this flight test to explore retrofit concepts of SVS display technology into existing glass cockpits (cockpits already equipped with raster-capable HDDs). One display configuration, referred to as the SVS Size A (5.25 in. wide by 5 in. tall), was similar to a B-757-200 electronic attitude direction indicator (EADI) with separate airspeed, altitude, and vertical speed gauges, with the addition of SVS information. The second HDD configuration, referred to as Size X (9 in. wide by 8 in. tall), featured an enlargement of an integrated Primary Flight Display (PFD) to replicate future SVS HDD concepts. Evaluation pilots could control the FOV of the HDD EADI and PFD concepts evaluated to enhance display effectiveness. A conventional Size A EADI HDD configuration with no SVS information was also provided as a baseline for comparison purposes. Terrain information was available on the Navigation Display (ND) (4.75 in. wide by 6 in. tall) for all of the concepts.

The objectives of the flight test were to:

a) Confirm potential of NASA SVS HUD concept as a retrofit solution for display of SVS concepts in non-glass cockpits. Determine potential in both day VMC and in day, low-visibility operational environments.
b) Confirm results from piloted simulation experiments and SVS-DFW flight test for operational utility and acceptability of various-sized (Size A, X) head-down synthetic vision displays.
c) Compare operational utility and acceptability of photo-realistic textured with generic textured terrain databases within NASA SVS concepts (HUD; head-down Size A, X).
d) Assess pilot path control performance (flight technical error) during manually flown landing approach and go-around maneuvers in a terrain-challenged operational environment, with and without SVS display concepts.
e) Determine required navigation performance capabilities of SVS for area navigation.
f) Confirm the situation awareness and workload benefits of SVS display concepts.
g) Provide demonstration of economic potential of SVS for approaches that have significant restrictions for current operations.

Hypotheses

The a priori hypotheses (based on prior SVS research) for the flight test evaluations included:

Objective Data Hypotheses

a) All SVS display concepts would have lower flight technical error (FTE) compared to a Baseline EADI/ND.
b) Pilots would have lower FTE with the SVS HUD concepts than with the Size X display concepts.
c) Pilots would have lower FTE with the Size X displays than with the smaller Size A SVS displays.
d) Pilots would have lower FTE with the photo-realistic texture concepts.

Subjective Data Hypotheses

e) Pilots would prefer all SVS display concepts over the Baseline EADI/ND.
f) Pilots would prefer the HUD over the Size X display concepts.
g) Pilots would prefer the Size X display concepts to the smaller Size A SVS display concepts.
h) All SVS display concepts would be rated higher in situation awareness than the Baseline EADI/ND.
i) Pilots would rate the Size X display concepts significantly higher in terms of situation awareness than the Size A SVS display concepts.

j) There would be an interaction found between display size and texture for situation awareness ratings. For example, photo-realistic texture would be judged to be much more effective than generic texturing on the HUD than on Size A, where texturing effects would be much less important.

k) Pilots would rate the photo-realistic texture concept significantly higher in terms of situation awareness than the generic texture concept for both HDD and HUD display concepts.

l) Workload ratings would be significantly lower for all SVS display concepts compared to the Baseline EADI/ND.

m) Workload ratings would be significantly lower for the HUD compared to the Size X display concepts.

n) Workload ratings would be significantly lower for the Size X compared to the Size A SVS display concepts.

o) Workload ratings would be significantly lower for the Size A SVS display concepts compared to the Baseline EADI/ND.

Method

Subjects

Six evaluation pilots, representing three airlines, FAA and Boeing, flew 12 research flights totaling 51.6 flight hours. Eighty-four data flight test runs were conducted to evaluate the NASA display concepts with forty-nine being flown to Runway 07 and thirty-five flown to Runway 25. All participants were rated B-757 captains with operating experience at EGE. The currency and degree of actual experience at EGE prior to the test varied but was not considered to be a significant factor since, prior to deployment, all evaluation pilots received a one-day training course (briefing and simulator session) at NASA LaRC. This training was to familiarize them with the SVS display concepts as well as provide sufficient training in the approach procedures and tasks to create a consistent level of knowledge and experience for EGE operations.

Simulator and Flight Test Vehicle

Aircraft. The flight test was conducted in an operationally realistic, terrain-challenged environment using the NASA LaRC Boeing 757 (B-757) ARIES aircraft to compare SVS display concepts to a Baseline EADI and navigation display (ND) which included a simulated TAWS. The left seat in the Boeing 757 was occupied by the Evaluation Pilot (EP). This position, with its associated displays and controls, is used for research testing and is known as the Flight Deck Research System (FDRS). The right seat was occupied by a NASA Safety Pilot (SP). The left seat included the installation of an SVS Research Display (SVS-RD) and an overhead HUD projection unit (see fig. 1). A vision restriction device (VRD) (fig. *2*) was placed in the left-seat forward windscreen to block the EP's forward vision and thus simulate IMC when needed experimentally.

Figure 1. SVS-RD installed in ARIES 757 aircraft.

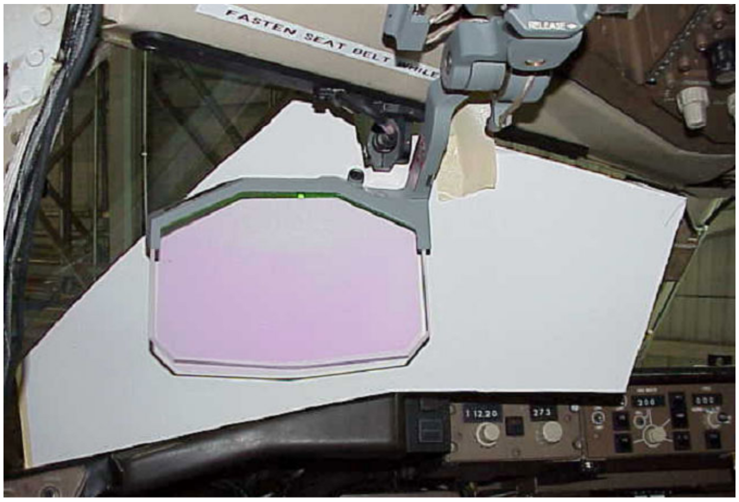


Figure 2. Vision Restriction Device in ARIES 757 aircraft.

SVS-RD. The SVS-RD was a Commercial Off-the-Shelf 18.1 in. diagonal high brightness Liquid Crystal Display monitor, modified for installation over the forward instrument panel cluster on the left hand side of the ARIES cockpit (see fig. 1). Since the SVS-RD was capable of generating high resolution, multi-sized displays, this monitor displayed all head-down display concepts for evaluation. The SVS-RD covered the normal Boeing 757 captain's displays with the exception of the analog standby instruments (attitude direction indicator, airspeed, and altitude). The SVS-RD had 1280 vertical x 1024 horizontal pixel resolution (approximately 90 pixels per inch) with 900 nits brightness for reasonable sunlight readability in the Boeing 757 aircraft. Overall, the SVS-RD weighed approximately 16 lbs.

Field of View Control. FOV control for the NASA HDD SVS concepts was available to the pilot on a four-position wafer switch on a conveniently located center console panel. The FOV options were: Unity, 30º, 60º, and 90º. The FOV provided at the ”unity” setting changed depending upon the size of the experimental HDD condition being flown.

Synthetic Vision Systems Graphic Engine (SVS-GE). The NASA SVS display concepts were generated by two Intergraph Zx10 personal computers using Windows NT ™. The Zx10 used for this flight test was a dual 866 MHz Pentium® III processor with 1+ Gigabytes of Random Access Memory. The video card used was a 3D Labs, Inc. Wildcat™ 4210 which provided 1280x1024 resolution at 60 Hertz (Hz) anti-aliased (SuperScene ™ enabled) video rendering at real-time (>30 Hz) update rates. Symbology was generated using the OpenGL application programming language. SXGA (1280x1024 pixels, 60 Hz non-interlaced) format video output from the Zx10 computer drove the SVS-RD. For the HUD raster channel, an XGA (1024x768 pixels) image from the Zx10 was scan converted to RS-343 (875 line, 30 Hz interlaced) format video via a Folsom 2100 scan conversion unit.

Head-Up Display. The left-seat, overhead Dassault projection HUD was interfaced with a research Flight Dynamics Head-Up Guidance System® (HGS)-4000 computer. The HGS-4000 was modified by NASA to conduct research on certain HUD configurations. The HGS-4000 could be placed in a "Normal" mode, which triggered the HGS-4000 to function with its nominal commercial functionality, or in a “Research” mode. For this flight test, the HGS-4000 was operated in the “Research” mode which triggered the HGS-4000 to include some special purpose symbology, as described below.

The HGS-4000 computer is stroke-on-raster capable using an RS-343 raster video format input. The HGS-4000 raster input consisted of the synthetic vision (SV) terrain and tunnel symbology while retaining high-quality stroke symbology for primary flight information (e.g., airspeed, altitude). The HGS-4000 “Primary Mode” stroke symbology set was used in the flight test, albeit with the compass rose symbol set removed when in “Research” mode. The raster image consisted of “layers” of imagery and symbology (see fig. 3). Synthetic terrain imagery formed the “Background Raster”. Guidance symbology and tunnel (“Pathway-in-the-Sky”) symbology were combined to create the “Foreground Raster”. The FOV of the ARIES HUD was measured to be 22º vertical by 28º horizontal. Note that to maintain conformality with the outside world, the FOV for the HUD raster image was fixed and could not be varied by the EP. As the minification/magnification factor was thus unity, the condition was colloquially known as unity FOV.

Brightness and contrast controls were provided: a) Stroke-only brightness; b) Overall raster image brightness; c) Background raster (synthetic terrain imagery) contrast; d) Background raster brightness; and e) Foreground raster (guidance and tunnel symbology) brightness. Although somewhat complex, these controls gave the EP the needed flexibility to tailor the image.

A HUD declutter button was available on the control yoke. The declutter button cycled the HUD symbology between four modes: 1) No declutter – All display elements present; 2) Foreground raster (raster guidance symbology & tunnel) removed; 3) All HUD raster removed; and, 4) All display elements (both stroke and raster) removed.

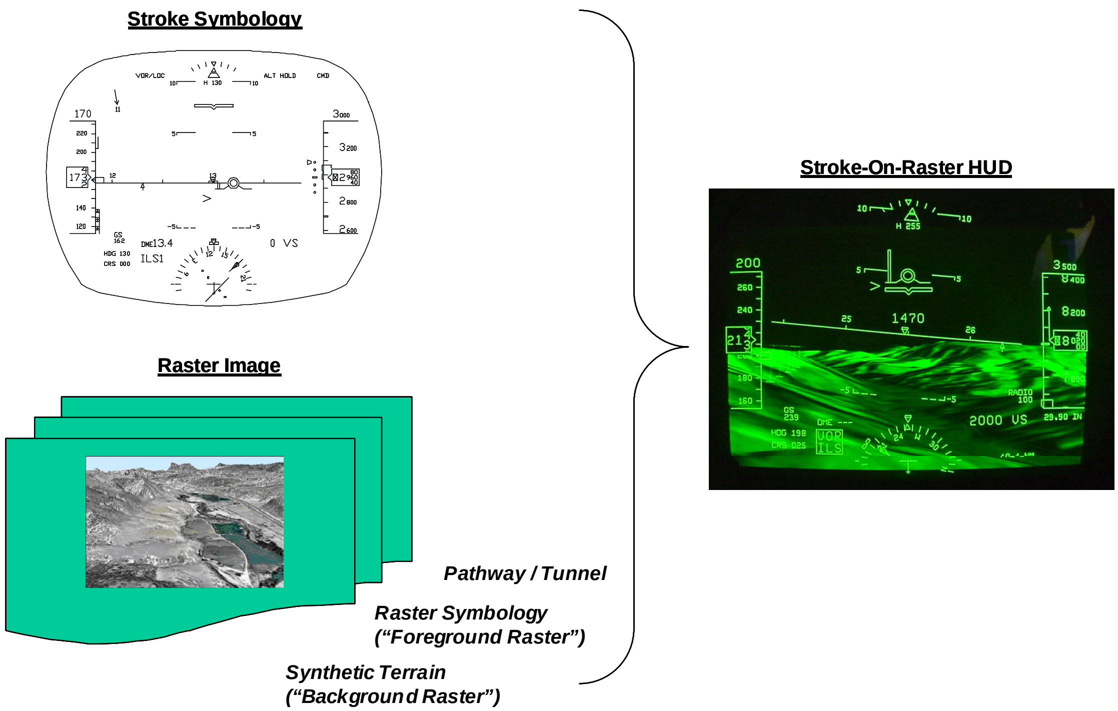


Figure 3. HUD stroke-on-raster imagery components.

Ground-based facilities

Flight Systems Integration Lab (FSIL). The Flight Systems Integration Lab (FSIL) at NASA LaRC was used to validate the experimental systems. By simulating the aircraft systems in flight conditions, data passing through the network devices was monitored, verifying that the test system and data collection was functioning properly. Evaluations in the FSIL environment were used to establish satisfactory performance of the HGS-4000 system. Satisfactory performance was defined as the ability to draw flight guidance symbology and raster imagery, provided by the SVS computers and forward-looking infra-red (FLIR) cameras, on the HUD combiner glass.

Integration Flight Deck (IFD). The Integration Flight Deck (IFD) at NASA LaRC was used to develop and evaluate key hardware and software components, as well as provide familiarization and training for the flight crew prior to the EGE deployment. The IFD is a simulation facility which emulates the ARIES research cockpit. The IFD has the same pilot controls as ARIES. Other significant features of the IFD are the 6-degrees of freedom B-757 simulation model, mode control panel, and realistic replication of the FDRS. It also includes a representative ARIES Boeing 757 Flight Management System (FMS), which contains the published routes to EGE (i.e., the FMS approaches, departures, and missed approaches), and pilot-FMS interface controls simulation, including autoflight systems.

Evaluation Tasks

In general, flight-test operations involved established operational maneuvers employed by airlines operating at EGE. The base of operations for deployment was Colorado Springs (COS) municipal airport, located approximately 115 nm from EGE. COS provided minimal operational restrictions due to air traffic, and easy access to aircraft and personnel support facilities. All of the checkout and research flight activities occurred at EGE (see fig. 4).

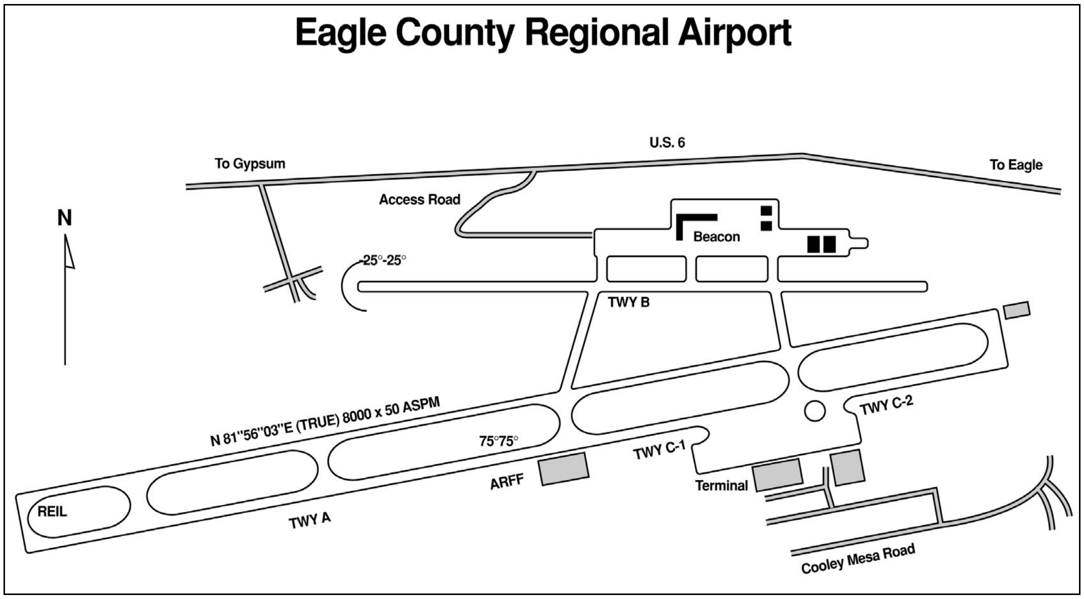


Figure 4. Diagram of Eagle-Vail regional airport.

Although EGE has received a “Special Airport” designation from the FAA, approach and landing procedures are not atypical of many airports constrained by terrain in all quadrants. Precision approach landing aides are not available due to the terrain. EGE is only equipped with an offset localizer with Distance Measuring Equipment (DME) (~1 degree offset from the runway heading) to support Localizer-DME Approach (LDA) procedures which includes several altitude step-downs. Visual arrivals to both EGE runways (07 and 25) are commenced from the East using an LDA procedure. See figures 5 and 6 for photographs of the approach ends of the EGE runways.

Figure 5. Runway 25 at Eagle-Vail Regional Airport

Figure 6. Runway 07 at Eagle-Vail Regional Airport

To facilitate larger commercial airline operations, such as Boeing 757 aircraft, and obtain lower instrument approach minima, FMS-based approach and landing procedures have been developed and certified for EGE. These procedures also specify training and equipment standards that are well above that required for the FAA-published EGE instrument approach and landing procedures.

The evaluation tasks were developed by tailoring existing FAA-approved FMS-based approach and departure procedures for EGE. The tailoring defined procedures and constraints which aided in experimental data collection and subsequent data analysis. Two approaches and associated departure tasks were flown during day VMC. (See figures 7 and 8.)

FMS Runway 25 Approach and Cottonwood-2 Departure ("FMS25"). The FMS25 task started on a dogleg to the final approach course, level at 13,100 ft MSL (step C in fig. 7). At the waypoint TALIA, approximately 16 nm from the airfield – the final approach fix – the turn to the localizer approach course was made and the descent into the EGE local operating area was initiated. The initial descent angle from TALIA was nominally 4.43 degrees. Several descent angle changes were commanded until approximately 1000 ft Above Field Level (AFL), where the guidance directed a 3 degree descent to the runway touchdown zone. A go-around was declared before 200 ft Above Ground Level (AGL) and the NASA SP took over control of the 757 from the EP (step I in fig. 7). The subsequent missed approach was, in fact, tailored to mirror a "worse-case" terrain-clearance departure; hence, the wording "missed approach" and "departure" are often interchanged throughout this document, yet they apply to the same task. After the go-around call, the SP performed a level-off, flew at a constant AGL over the runway, and reconfigured the aircraft for the climb-out. At approximately mid-field, a left turn (step J in fig. 7) was made to pick up the nominal FMS-departure path (the Cottonwood-2 departure) - well before the departure end of the runway to ensure clearance from Snow Mountain – an 1800 ft AFL peak approximately two nautical miles (nmi) from EGE. After the departure turn, the EP was given control of the aircraft and flew the Cottonwood-2 departure task. A reduced climb angle departure, loosely replicating the climb of a moderately loaded 757 in a single engine condition, was flown. The simulated single engine departure provided a worst-case operational scenario but a best-case condition for terrain awareness testing. The simulated single-engine Cottonwood-2 departure required a turn at Waypoint F219G (step L in fig. 7) to maintain terrain and obstacle clearance along Cottonwood Pass. The departure concluded upon reaching 10,000 ft MSL which typically occurred just prior to Waypoint F204K (step M in fig. 7). No departure tunnel was provided, and the EP flew conventional lateral path and speed-on-pitch guidance symbology for all display concepts.

Visual Arrival to Runway 07 and KREMM Departure ("Visual 07"). The Runway 07 approach task started with the same FMS25 approach procedure. At approximately 5.3 nmi DME (step G1 in fig. 8), a level off at 8100 ft MSL was commanded followed by an approximate 20 degree left turn (step H1) into a modified downwind leg. When about abeam the Runway 07 end, a descending right turn was flown for landing. For this flight test, a go-around was declared before 200 ft AGL and executed by the NASA SP. After the go-around call (step L1 in fig. 8), the SP took over control of the 757, performed a level-off and reconfigured the aircraft for the climb-out. Near the departure end of the runway, the task, following the published KREMM departure procedure, called for an initial left turn to a 050 heading (step M1 in fig. 8). After the departure turn, the EP was given control of the aircraft and flew the remainder of the departure task (where, again, the terminology "missed approach" and "departure" may be interchanged, yet they relate to this same task). A reduced climb angle departure was again established to provide a best-case testing condition. A 050 heading was held until intercepting the 059 radial from the Snow VOR (Very high frequency Omni-direction Radio) beacon. The run ended upon climbing along the 059 radial through 10,000 ft Mean Sea Level (MSL) (step Q1 in fig. 8). No departure tunnel was provided, and the EP flew conventional lateral path and speed-on-pitch guidance symbology for all display concepts.

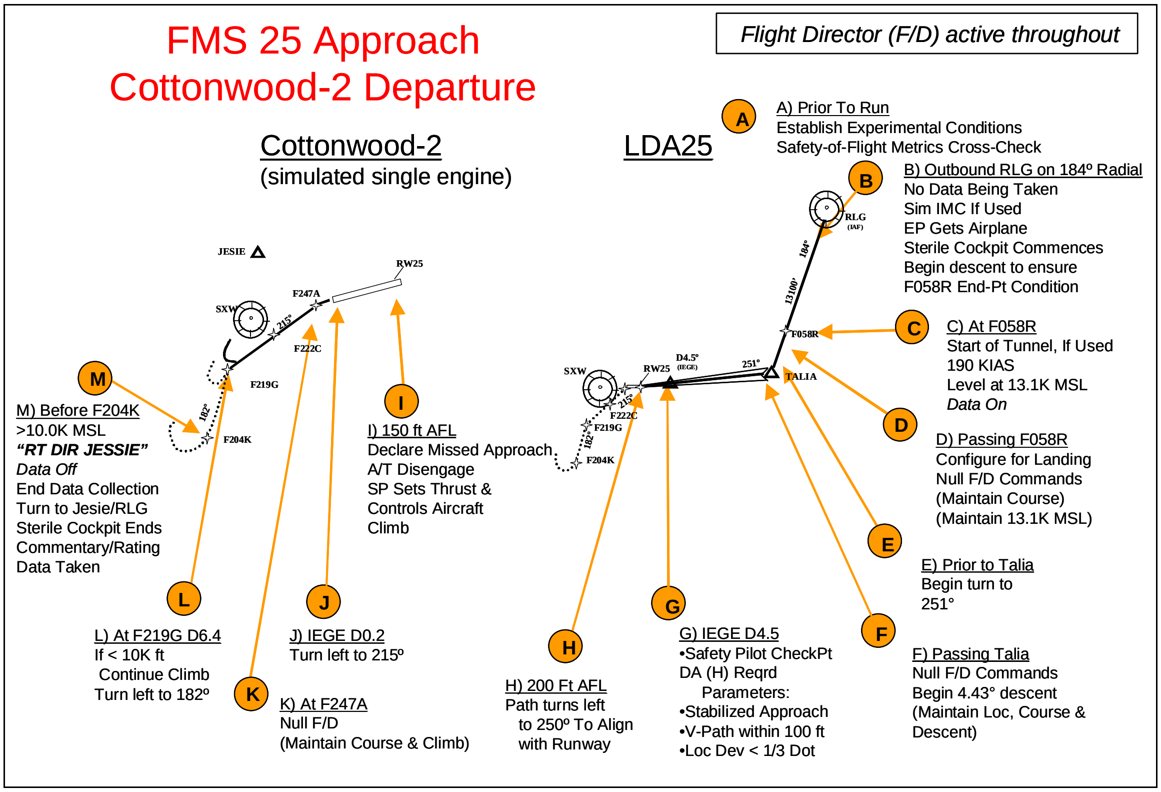


Figure 7. FMS Runway 25 Approach and Cottonwood-2 Departure

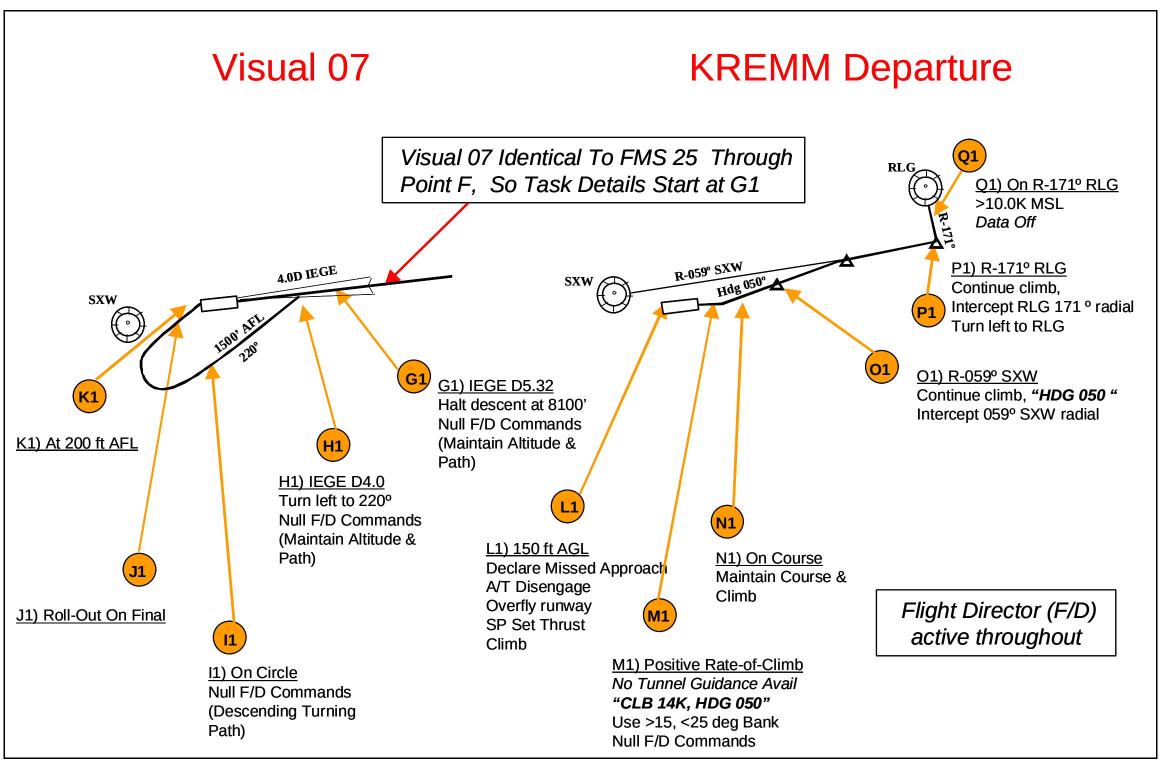


Figure 8. Visual Arrival to Runway 07 and KREMM Departure

Terrain Database

The terrain databases used for this experiment were 95 nmi by 95 nmi in area, centered at the EGE airport. Jeppesen provided the source elevation data for the EGE databases based on United States Geological Survey (USGS) National Elevation Dataset (NED). The delivered elevation data was 1-arcsecond (30 meter) in Digital Elevation Model (DEM) format, with a Universal Transverse Mercator (UTM) WGS84 projection and covered a 100 nmi square geographic area centered about EGE. The accuracy of the source data was within 12 meters (90% of data) horizontal and 7 meters (90% of data) vertical. From this DEM, four real-time rendering databases were created (see fig. 9): SVS-HDD full color elevation-based (generic) textured, SVS-HDD full color photo-realistic textured, SVS-HUD monochrome green elevation-based (generic) textured, and SVS-HUD monochrome green photo-realistic textured. The monochrome databases were created because the HUD is monochrome. The monochrome databases were designed specifically for the monochrome HUD to ensure proper rendering (i.e., no holes in database due to lack of green color). Each EGE terrain database was built using the Terrain Experts, Inc (Terrex) TerraVista Pro™ software. The SV terrain databases were written to a UTM Terrex TerraPage™ format and rendered using CG2 VTree.™ An EGE airport model was created using Multigen™ Creator modeling software and placed into the SV database.

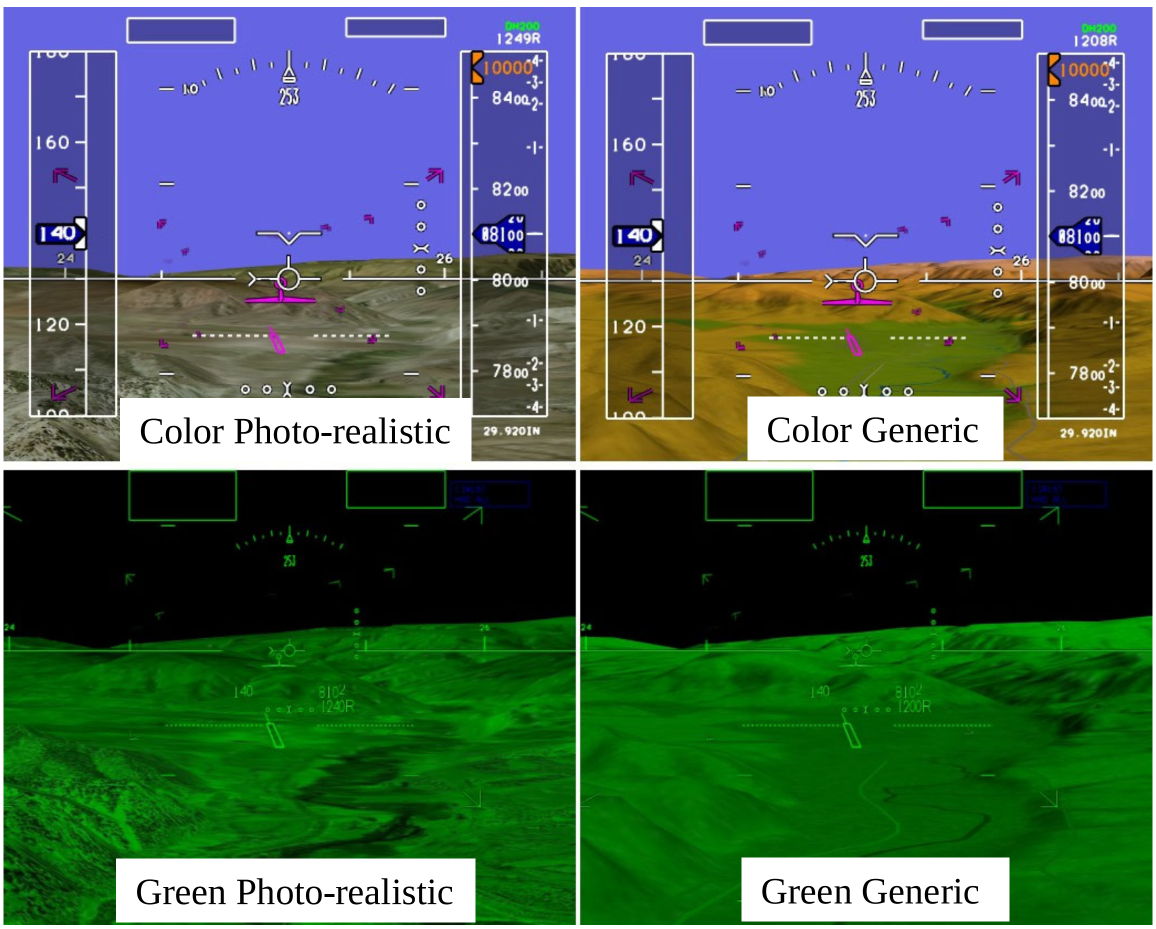


Figure 9. Four databases with symbology overlays used for the experiment.

To create the full color photo-realistic terrain database, multi-resolution aerial imagery (geotiff ranging from 2 to 16 meters/pixel) was overlaid on the DEM database. The source data included three image sets of 1, 4, and 16 meter resolution (see table 2). The final TerraPage™ database was created from the source data (table 3) after a rendering trade off study. The trade off study maximized the amount of texturing to be rendered (most photo-realistic) while maintaining a 30 Hz update frame rate. A significant effort was made to color balance the various aerial images to produce a non-tiled, single brightness and contrast database appearance. To create the monochrome green photo-realistic database, full color aerial photographs were converted to a single green color using a freeware image-editing tool, ImageMagick.

Table 2. Photo-realistic Image Sources

Image resolution	**Provider**	**Format**	**Area Coverage (centered on EGE)**
1-meter per pixel	NGS	WGS84 UTM Zone 13	17.2 nmi (east/west) by 6.8 nmi (north/south)
4-meter per pixel	ImageLinks	geotiff WGS84 UTM Zone 13	29.7 nmi (east/west) by 32 nmi (north/south)
16-meter per pixel	ImageLinks	geotiff WGS84 UTM Zone 13	104.2 nmi (east/west) by 104.2 nmi (north/south)

Table 3. Final TerraPage Database Created from Source Data

Image Resolution	**Coverage**
2-meter per pixel	2.1 nm by 0.7 nm
4-meter per pixel	25 nm by 25 nm
16-meter per pixel	95 nm by 95 nm

To create the generic textured terrain database, a color mapping technique (i.e., “elevation shading”) was developed. The color scheme was based on Aeronautical Chart legends with slight modification to show more contrast over the elevation range in the database. The colors ranged from greens at the field elevation of EGE, to browns, to light tans, to off-white, with the greens representing the lower elevations bands, and the off-white representing the highest elevation band. Twelve bands were used, segmented into 250 meter ranges. To create the monochrome green generic database, shades of green were used to represent elevation changes. The green color intensities associated with each elevation level varied in an incremental fashion from the lowest to highest level. Thus, no two elevation levels had the same green value. Main cultural features, such as railroads, roads, lakes, and rivers, were placed in the generic textured terrain databases.

Display Concepts

The flight test was designed as a comparative study against a baseline condition. The Baseline was representative of the current display configuration being flown in regular airline service to EGE – the Boeing 757 EADI format with a TAWS-capability installed on the Navigation Display. The TAWS aural alerts were not implemented, as continual aural alert conditions were anticipated. In the actual test conditions, even the ship’s conventional Ground Proximity Warning System aural alerts had to be disabled.

The Baseline display (fig. 10) was rendered on the SVS-RD. As evident in Figure 10, the Baseline EADI was intentionally not a direct replication of the Boeing 757 EADI but instead, was a blue-over-brown representation of the NASA SVS concepts. The intent was to keep the display’s symbolic information constant (e.g., pitch ladder) in the comparison across display concepts to avoid additional variability. Also note that the ND is not directly below the EADI. The ND was offset because the control yoke blocked the view of the display directly below the EADI. The TAWS ND display format was constant across all concepts.

Six NASA SVS concept display configurations were evaluated (SVS-HUD, SVS-HDD Size A, and SVS-HDD Size X, each with generic and photo-realistic terrain). A comparison of these displays (figs. 11-15) with Figure 10 – the Baseline display configuration – shows the intuitive nature of the SVS display portrayal for terrain awareness. The HUD concepts utilized the Baseline concept head down, along with the TAWS ND.

In addition to terrain texture differences, several important symbology differences were embedded in the SVS configurations. These symbology differences did not influence the terrain awareness properties of the display configuration evaluation but did influence the pilot's ability to precisely monitor and control the aircraft. These differences include the airspeed and altitude format (e.g., "round-dials" on the Baseline and Size A concepts versus "tapes" on the Size X and HUD concepts), the presence (on SVS concepts) or absence (on Baseline) of a flight path marker (also referred to as the velocity vector), and the presence (on SVS concepts) or absence (on Baseline) of tunnel or "pathway-in-the-sky" information. It should be noted that raw data (path) indicators were provided on the glideslope and localizer deviation scales for all the display concepts (Baseline and SVS). These raw data indicators are referred to as "dogbone" indicators (see fig. 16).

A tunnel was nominally drawn for approach guidance on the SVS-HUD and SVS-HDD (but not for the Baseline display condition) to increase the pilot's awareness of the desired aircraft trajectory. The objective was to create path awareness yet not to obscure or occlude the terrain portrayal of the Synthetic Vision image. With this objective, a "minimalist" tunnel was constructed using "crow's feet" and "goal posts" (see fig. 17). The crow's feet represented the truncated corners of nominally-connected 2-dimensional rectangles spaced at 0.2 nm increments along the desired path. The top crow's feet of the tunnel were only displayed up to 1.0 nm in front of the aircraft. The bottom crow's feet were linearly decreased in brightness so, by 3.0 nm from own-ship, the brightness of the bottom crow's feet was reduced to zero. The goal posts were vertical lines anchored to the ground and were spaced at 1.0 nm increments along the desired path (also decreased in brightness, disappearing by 3.0 nm).

Additional guidance information for the SVS display concepts was provided by a ghost airplane symbol (see fig. 18). The ghost airplane was positioned by a modified form of pursuit guidance, documented in Merrick (1995), to keep the aircraft trajectory tracking the tunnel. Placing the flight path marker on the beacon of the ghost aircraft symbol guided the EP to the desired flight path. During the missed approach tasks, the tunnel and ghost aircraft were removed and a single cue flight director based on the ship's FMS was drawn to provide speed-on-pitch and roll steering commands (also presented on the Baseline EADI).

Because of difficulties encountered with the ship systems' FMS and flight director, approach guidance for the Baseline Concept varied according to Task. For the FMS 25 approach task, flight director guidance was provided on conventional dual cue flight director needles. For the Visual 07 approach task, no flight director guidance was available, and the pilots resorted to the raw lateral and vertical path deviation indicators (dogbones).

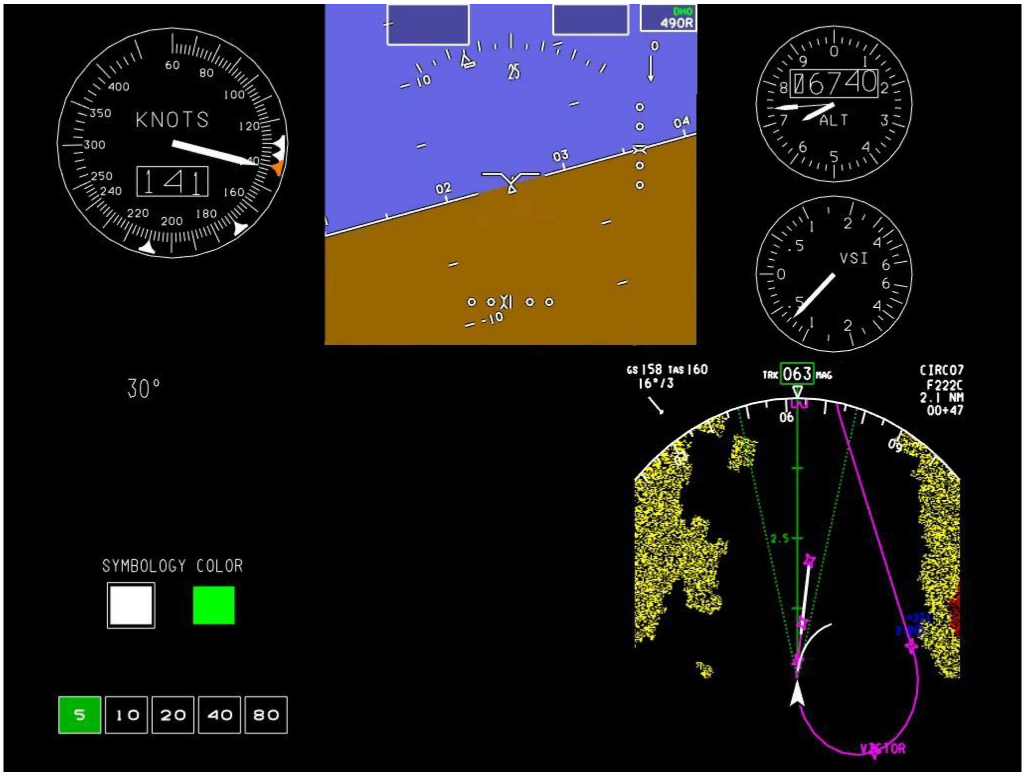


Figure 10. Baseline display, EADI with TAWS on ND.

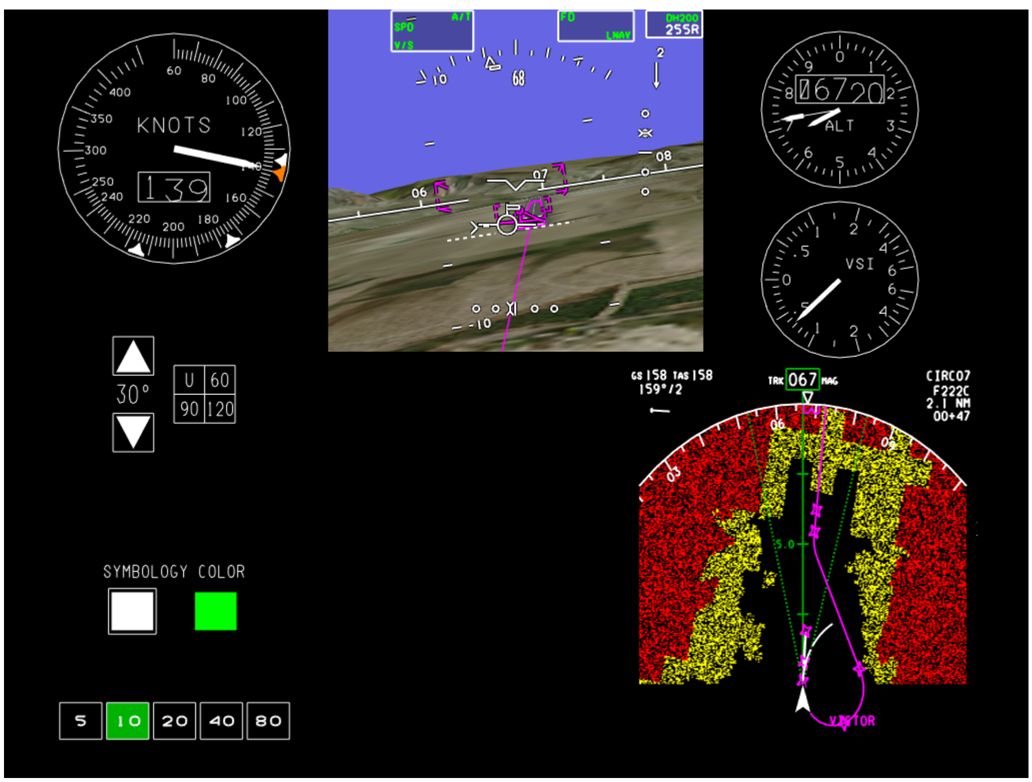


Figure 11. Size A with photo-realistic texturing.

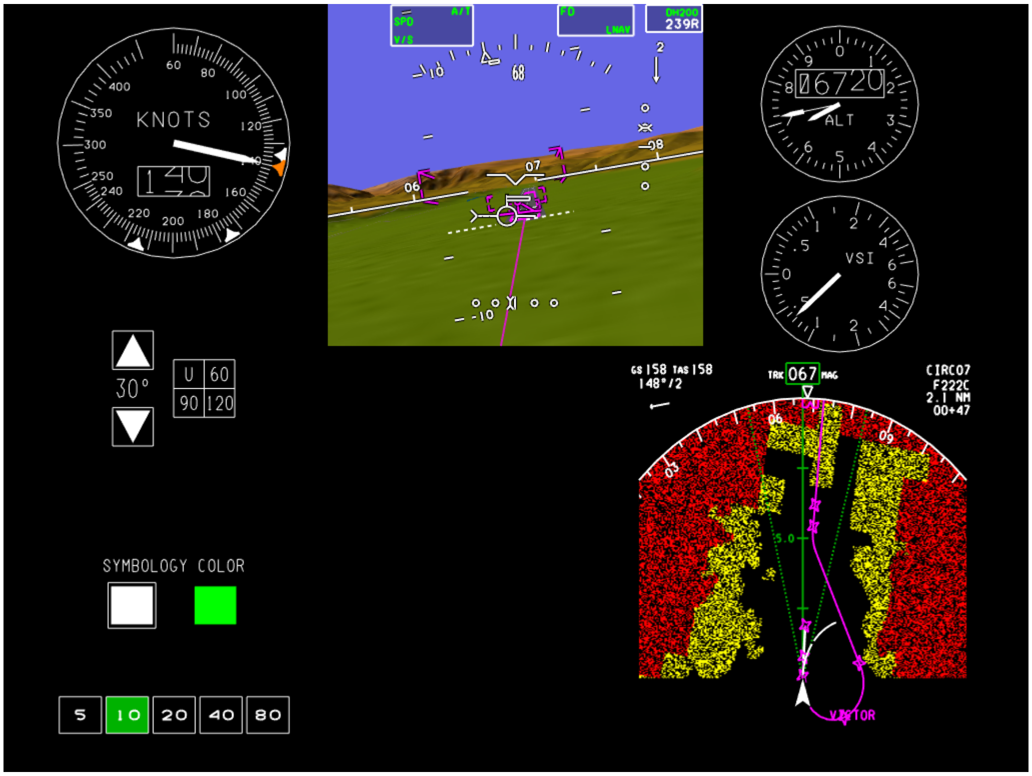


Figure 12. Size A with generic texturing.

Figure 13. Size X with photo-realistic texturing.

Figure 14. Size X with generic texturing.

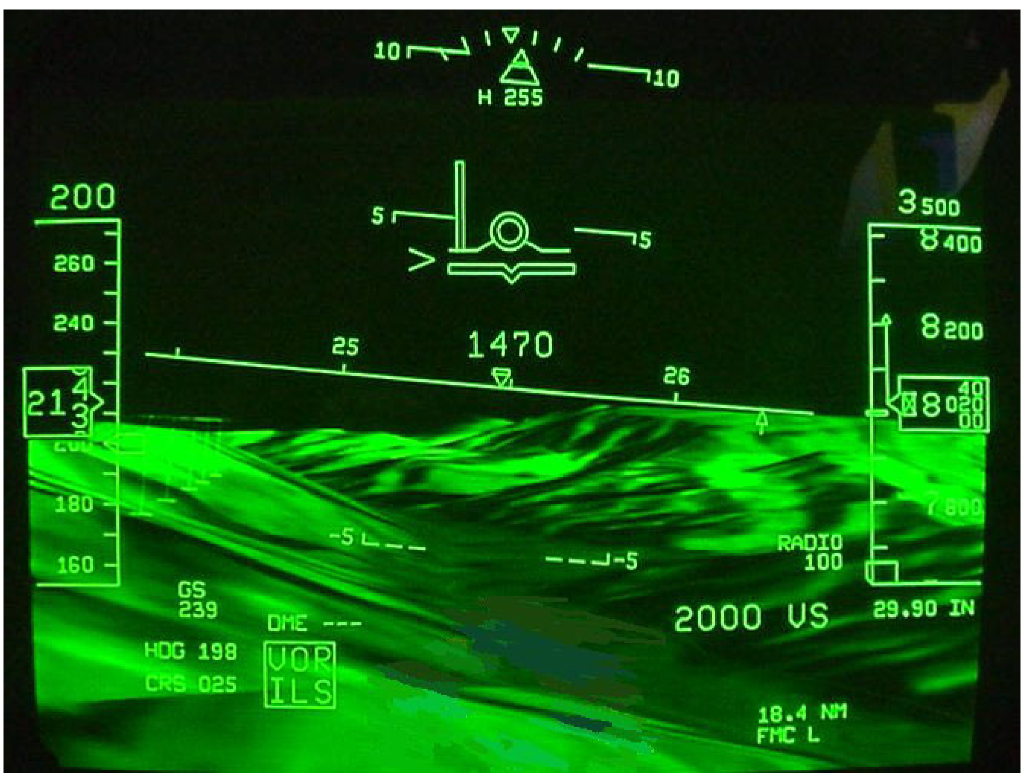


Figure 15. Head-Up Display with generic texturing

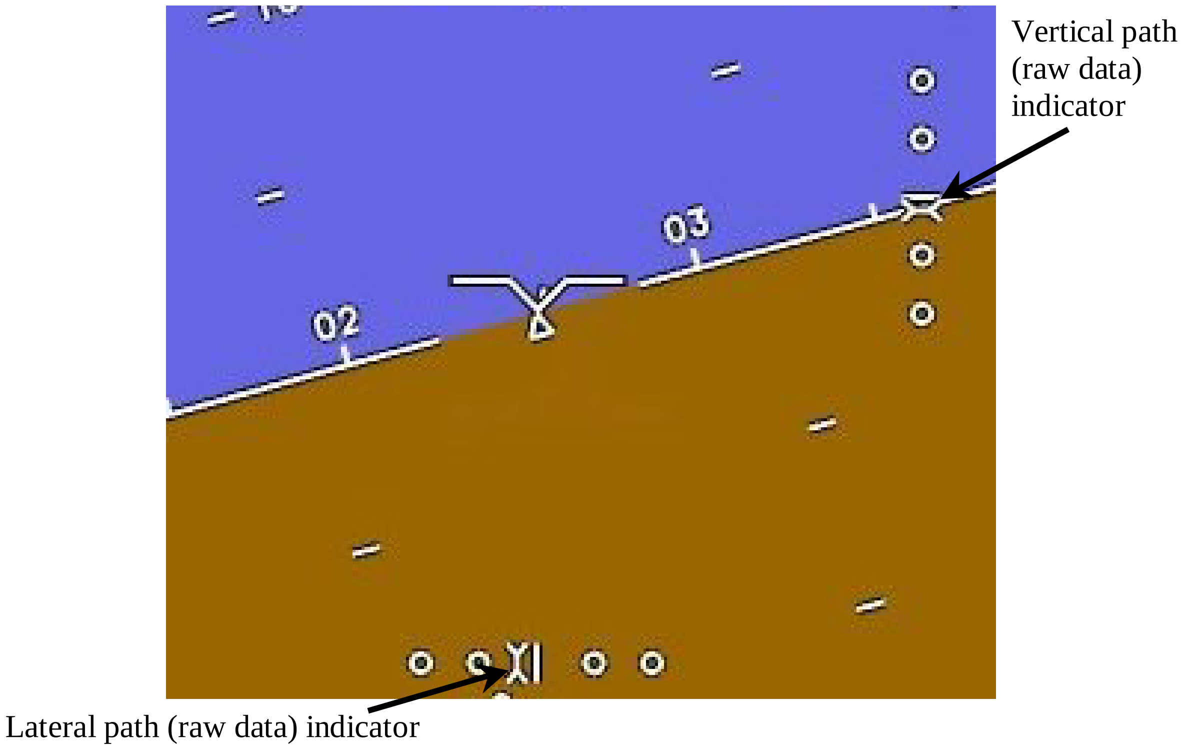


Figure 16. Raw data indicators for the Baseline and SVS concepts.

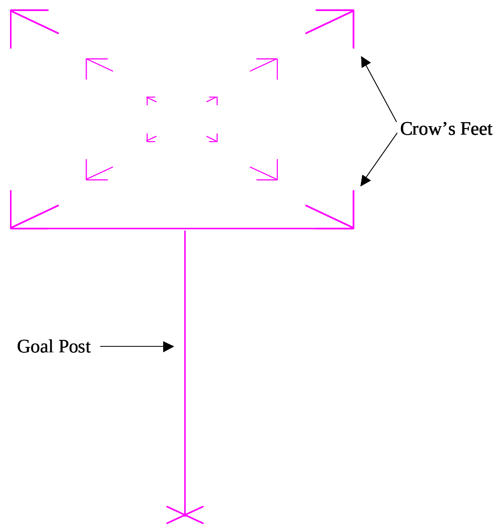


Figure 17. Crow's feet and goal post in the Synthetic Vision tunnel

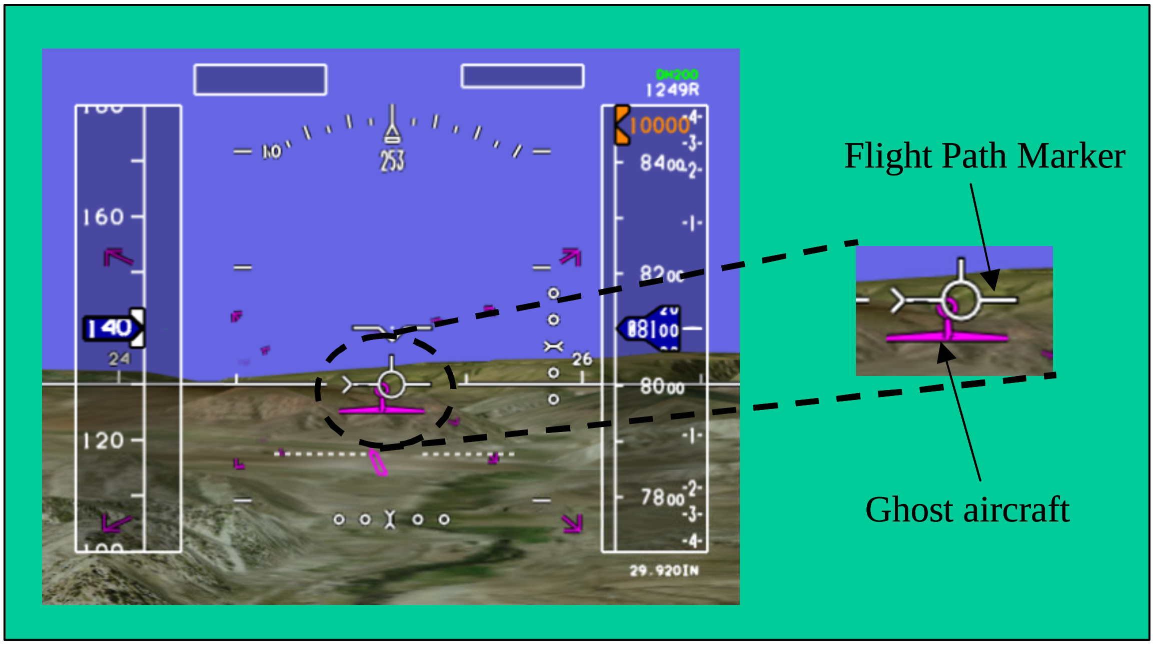


Figure 18. Ghost aircraft symbol

Experiment Design

A full-factorial experimental matrix design was established to evaluate the six NASA SVS display concepts (SVS-HUD, SVS-HDD Size A, and SVS-HDD Size X, each with generic and photo-realistic terrain) and the Baseline display condition in each of the two approach and departure tasks. Evaluations were flown under simulated instrument meteorological conditions using a VRD.

Independent Variables

For the full-factorial experiment, the independent variables were display type (HUD, Size A, Size X, EADI), terrain texturing method (photo-realistic, generic), and evaluation task (Visual 07, FMS25).

Dependent Measures for the Objective Data Analyses

Engineering unit data was collected on all evaluations. The approach and departure paths for the two flying tasks (FMS25 and Visual 07) were analyzed using a flight segment analysis approach (see table 4 and figures 19-20). Flight segments were used since the segments contain well-defined piloting tasks in which specific and clear performance expectations were given to the EPs, and control of statistical variability could thus be anticipated. The segment definition and analyses for Segments 1 and 2 were identical for both the FMS25 and Visual 07 tasks. The KREMM departure segments out of the Visual 07 task were not analyzed because the nature of the task was not conducive to a uniform flight conduct. The departure was not path-based (heading-based, rather than ground track) and not all of the runs, as actually conducted, used the exact same display configuration and flight director set-up. Therefore, analyses of these segments would have been more indicative of these differences than those of specific SVS-design parameters.

Table 4. Flight Segment Definitions and Associated Piloting Tasks

Segment Number	Segment Description	Associated Flying Task	Piloting Task	Guidance Available
1	Inbound to Waypoint TALIA	FMS25 & Visual 07	Maintain a straight course (no turns) while remaining level at an altitude of 13,100 feet MSL	Path deviation indicators on all concepts Baseline FMS25: Dual-cue flight director Baseline Visual 07: No flight director SVS FMS25 & Visual 07: Tunnel & ghost aircraft
2	Initial Approach	FMS25 & Visual 07	Maintain a straight course (no turns), and intercept and maintain the descent path	Path deviation indicators on all concepts Baseline FMS25: Dual-cue flight director Baseline Visual 07: No flight director SVS FMS25 & Visual 07: Tunnel & ghost aircraft
3	FMS25 Final	FMS25	Maintain a straight course (no turns) and a 3.0 degree descent path	Path deviation indicators on all concepts Baseline: Dual-cue flight director SVS: Tunnel & ghost aircraft
4	Cottonwood Departure Initial Climbout	FMS25	Null the flight director for the initial straight climbout	Baseline & SVS: Single-cue flight director
5	Cottonwood Departure Final Climbout	FMS25	Null the flight director for the final straight climbout	Baseline & SVS: Single-cue flight director
6	Circle Entry Level off	Visual 07	Level off at 8,100 ft MSL while maintaining a straight course (no turns)	Path deviation indicators on all concepts Baseline: No flight director SVS: Tunnel & ghost aircraft
7	Circle Dogleg	Visual 07	Maintain altitude while executing the dogleg left turn and then to maintain a straight and level course (no turns)	Path deviation indicators on all concepts Baseline: No flight director SVS: Tunnel & ghost aircraft
8	Circling Approach	Visual 07	Intercept and maintain the 3.0 degree descent path while executing the circling right turn to rollout on final	Path deviation indicators on all concepts Baseline: No flight director SVS: Tunnel & ghost aircraft

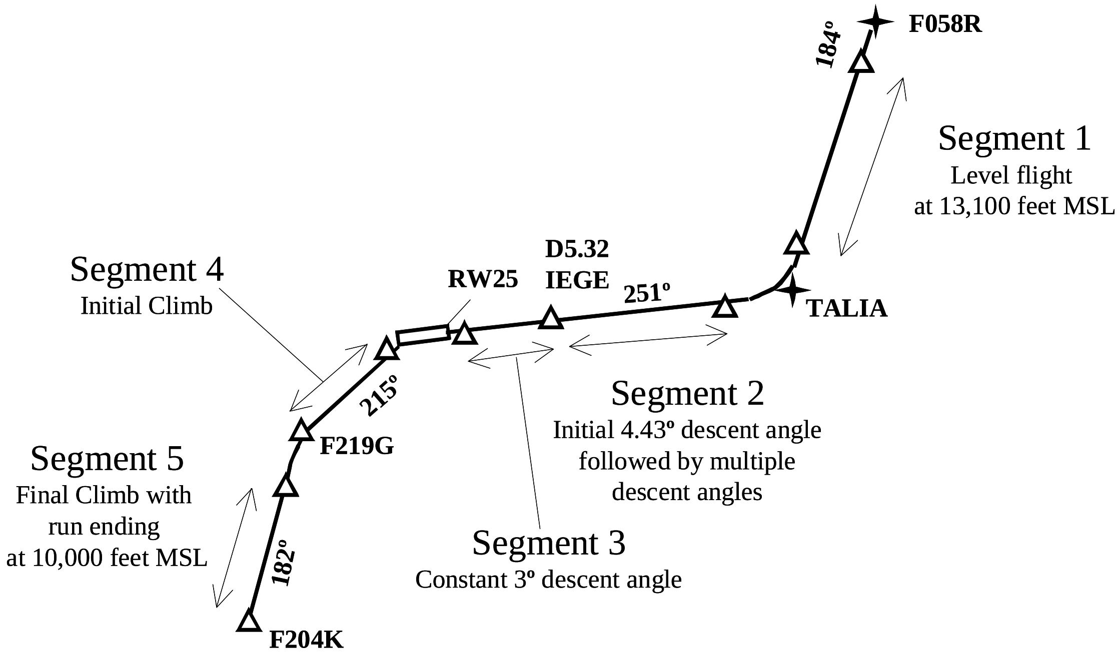


Figure 19. Segmentation of FMS Runway 25 Approach and Cottonwood-2 Departure for statistical analyses.

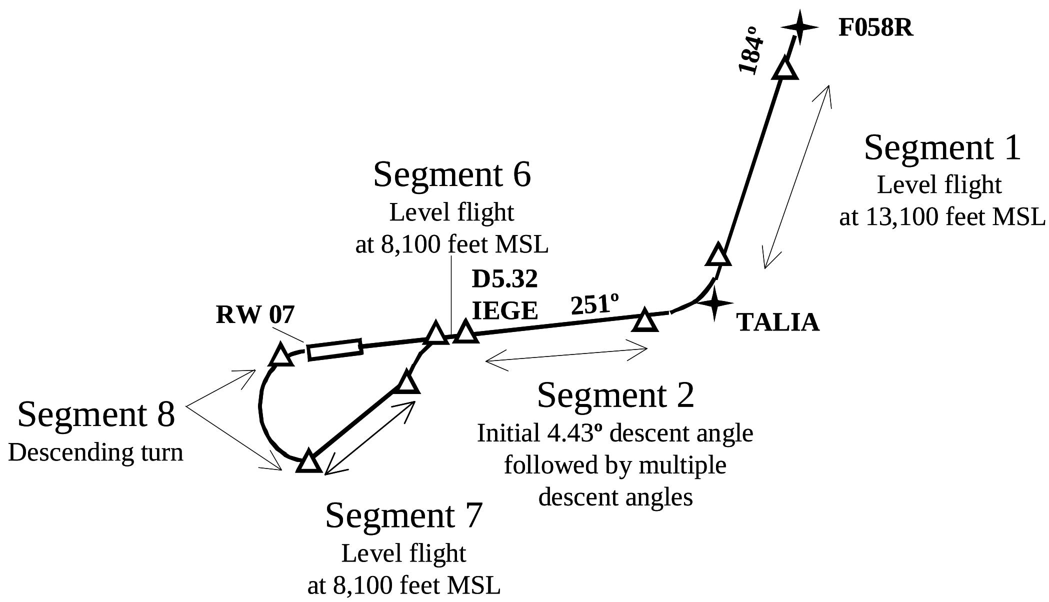


Figure 20. Segmentation of Visual Arrival to Runway 07 for statistical analyses

Root mean square (RMS) metrics were computed from the measures for vertical and lateral deviations of the B-757 from the defined path. The lateral path deviation data for the FMS25 approach runs using the Baseline display condition were not recorded properly. As such, this data were treated as missing variables in the analyses for the lateral path deviation measure. This mis-recording did not affect the analyses for the lateral path deviation for the Visual 07 flying task. Where available, RMS localizer error was also computed. When applicable, RMS flight director roll command and RMS flight director pitch command were also computed.

Analysis of the quantitative path data (RMS vertical and lateral deviation) were done by Task Segments and for the entire Approach. The entire Approach data included more than just the combination of the segment data for an approach, as some turns and some glideslope transitions were excluded from some of the segments by definition. The entire Approach data covered all points of the approach, from TALIA through to the missed approach point.

The data were analyzed by Analysis of Variance (ANOVA) across subject, display type, texture type (when appropriate), and flying task. Pilot selectable FOV effects on the quantitative path data for the HDDs were not examined for either the individual task segments nor the entire approach task, but rather were accepted as a standard component of the SVS HDD display types. Within the ANOVAs, only main effects and second order interactions were tested. Higher order interactions were pooled into the experimental error term. For statistically significant factors revealed by the ANOVAs, Student-Newman-Keuls (SNK) tests (at a 5-percent significance level) of individual means were performed at appropriate stages in the analyses.

FTE computations (which are one component of RNP calculations) were made from the recorded quantitative path error data for the Runway 25 and 07 approaches. These data were analyzed over the entire approach segment using histogram analyses. For lateral path performance, 27 bins were defined. Table 5 provides the bin width definitions used for the lateral path performance. For vertical path performance, 13 bins were defined. Table 6 provides the bin width definitions used for the vertical path performance. The bin values were selected to range across current-generation aircraft RNP values (≥ 0.1 nmi) with finer gradation below these values in case the advance tunnel guidance concepts provided measurable improvement in FTE. The number of occurrences in each bin was totaled and this total bin value was divided by the total number of occurrences over the entire approach to determine the percentage of occurrences for each bin to form the histograms.

Table 5. Lateral Navigation Performance Bin Definitions

Bin Number	Lateral Navigation Performance Range Window, x (nmi)
1	x>2.0
2	2.0≥x>1.5
3	1.5≥x>1.0
4	1.0≥x>5
5	.5≥x>.45
6	.45≥x>.4
7	.4≥x>.35
8	.35≥x>.3
9	.3≥x>.25
10	.25≥x>.2
11	.2≥x>.15
12	.15≥x>.1
13	.1≥x>.05
14	.05≥x>-.05
15	-0.05≥x>-0.1
16	-0.1≥x>-0.15
17	-0.15≥x>-0.2
18	-.2≥x>-.25
19	-.25≥x>-.3
20	-.3≥x>-.35
21	-.35≥x>-.4
22	-.4≥x>-.45
23	-.45≥x>-.5
24	-.5≥x>-1.0
25	-1.0≥x>-1.5
26	-1.5≥x>-2.0
27	-2.0≥x

Table 6. Vertical Navigation Performance Bin Definitions

Bin Number	Vertical Navigation Performance Altitude Window, x (feet)
1	x>300
2	300≥x>250
3	250≥x>200
4	200≥x>150
5	150≥x>100
6	100≥x>50
7	50≥x>-50
8	-50≥x>-100
9	-100≥x>-150
10	-150≥x>-200
11	-200≥x>-250
12	-250≥x>-300
13	-300≥x

Dependent Measures for the Subjective Data Analyses

Qualitative EP ratings and comments were collected both 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 (fig. 21) was provided aurally to the EP to elicit his comments after each run. In-flight comments were obtained between research maneuvers from the EP once aircraft control was transferred to the safety pilot. Post-flight qualitative EP ratings and other comments were obtained during extensive debriefings (semi-structured interviews) conducted immediately following a research flight on the ground at COS.

RUN QUESTIONAIRE

STRONGLY DISAGREE	MODERATELY DISAGREE	SLIGHTLY DISAGREE	SLIGHTLY AGREE	MODERATELY AGREE	STRONGLY AGREE
1	2	3	4	5	6

1.) IT WAS EASY TO DETERMINE AIRCRAFT POSITION WITH RESPECT TO THE TERRAIN: ________

COMMENTS: ____

2.) I WAS CONFIDENT IN THE TERRAIN INFORMATION CONVEYED BY THE DISPLAY: ________

COMMENTS: ____

3.) IT WAS DIFFICULT TO INTERPRET THE GUIDANCE CUES: ________

COMMENTS: ____

4.) IT WAS DIFFICULT TO FOLLOW THE GUIDANCE CUES: ________

COMMENTS: ____

5.) THE AMOUNT AND DENSITY OF DISPLAY INFORMATION WAS APPROPRIATE TO THE TASK: ________

COMMENTS: ____

6.) I COULD PERFORM THIS TASK WITH EASE AND PRECISION: ________

COMMENTS: ____

7.) AS I PERFORMED THE TASK, THE EFFECTS OF WIND AND TURBULENCE WERE INCONSEQUENTIAL TO THE EVALUATION: ________

COMMENTS: ____

==

- WERE ANY EVALUATION RATINGS SIGNIFICANTLY DIFFERENT BETWEEN THE APPROACH AND DEPARTURE TASKS?
- OTHER COMMENTS / REMARKS / SUGGESTIONS?

Figure 21. In-flight run questionnaire.

In addition to pilot ratings and comments, the Situational Awareness – Subjective Workload Dominance (SA-SWORD) technique (Vidulich & Hughes, 1991) was administered at the conclusion of the EP's flights during their semi-structured interviews. The SA-SWORD technique uses judgment matrices to assess situation awareness.

Organization of Trials

Approximately six evaluations per flight were planned. Each evaluation consisted of the approach and departure task to either Runway 25 or Runway 07. For aircraft performance considerations (fuel weight), Runway 07 evaluations were planned for the latter portions of each flight. Because of the desire to ensure collection of HUD flight test data, the HUD runs were always flown first of all the SVS display concepts. The experimental run matrix was developed with these constraints in place. See Appendix E for the planned run matrix.

Generally, an EP's first experimental run used the Baseline concept with no VRD installed. In fact, whenever the Baseline condition was evaluated, the VRD was not installed. The second experimental run used the HUD without the VRD installed. After the first two experimental runs were flown, the VRD was installed and used for the remaining display concept evaluations (except for the Baseline condition). The first three runs were always FMS25 runs to ensure some fuel weight reduction before attempting the more challenging Visual 07 runs. The SVS Size A and X concept runs, along with SVS texture type variations, were balanced across pilots in the usual manner to alleviate learning and fatigue effects.

Procedure

Upon arriving at Colorado Springs, the EP was given a briefing by a Synthetic Vision Display Concepts (SVDC) Principal Investigator before flying the ARIES aircraft. The briefing included the following elements:

- NASA Synthetic Vision Systems Project overview
- SVDC EGE flight test objectives
- EGE FMS-based approaches and departures
- SVS display concepts
- EGE approach procedures
- Experimental Equipment
- Schedule

The tests were not conducted in the blind for the EPs. All test conditions were briefed to the EP and the conditions had previously been flown in simulator training. Following the orientation briefing, a pre flight briefing was held where weather conditions and general aircraft operating procedures (e.g., communications, cockpit protocol, etc.) were discussed. A final general briefing was provided on the aircraft by the flight test director covering the sequence of maneuvers to be performed and the anticipated general schedule. ARIES flights originated at COS and transitioned to EGE for repetitive approach and departure maneuvers. ARIES transited back to COS at the end of research operations. Each flight was approximately four hours.

Results

Objective data results are presented from ANOVAs and histogram analyses, and the subjective data results are presented from ANOVAs, along with any pilot comments that were considered to be particularly meaningful. From the ANOVAs, results for the main factors and second order interactions of interest are presented. Since the main factor of pilot is usually significant in these types of analyses, it is not specifically mentioned in the Results section unless it was found to be not significant. Within the ANOVAs, only main effects and second order interactions were tested. Higher order interactions were pooled into the experimental error term. For statistically significant factors revealed by the ANOVAs, SNK tests (at a 5-percent significance level) of individual means were performed at appropriate stages in the analyses.

In addition, the unavailable lateral path deviation data for the Baseline condition FMS 25 runs were treated as missing variables for the task factor in the ANOVA analyses for this measure. As a result of the desire to eliminate any effects of this missing data for the Baseline Concept from the examination of the SVS displays, two separate ANOVAs were conducted on the quantitative path data for the individual task segments and the entire approach task. The first ANOVA treated display type (Baseline, Size A, Size X, HUD), task (FMS25, Visual 07), and pilot as the independent variables, while the second ANOVA treated SVS display type (Size A, Size X, HUD), texture type (generic, photo-realistic), task (FMS25, Visual 07), and pilot as the independent variables. Note that the second analyses are essentially a subset of the previous ANOVA treatments, but without the Baseline data and with different statistical degrees of freedom and power. Also, the second analyses enabled testing the texture type factor as well.

Approach Path for FMS25 and Visual 07

The analyzed approach path began at the end of Segment One (just prior to the turn at Waypoint TALIA), included all turns and glideslope changes thereafter, and ended at the point where the SP took over control of the aircraft (before 200 ft AGL).

Six runs (4 HUD, 1 Size A and 1 Baseline) were not included in these analyses due to known data contamination problems (operational restrictions, equipment problems, raster guidance symbology limitations, and cockpit distractions). For example, two HUD runs were excluded due to a low cloud ceiling of 12,500 feet MSL that prevented the pilot from flying the required altitude of 13,100 feet MSL during the inbound approach to Waypoint TALIA (operational restriction). Another HUD run was excluded due to a pilot's inability to discern the raster guidance symbology from the raster terrain, which caused him to miss the initial descent at Waypoint TALIA (symbology limitation). This raster clutter problem (which could have been eliminated with a programmable stroke symbology capability) was overcome once pilots had become familiar with the condition.

Display/Task Analyses. Separate ANOVAs were performed on the RMS lateral path deviation and the RMS vertical path deviation for the entire approach with display type (Baseline, Size A, Size X, HUD), task (FMS25, Visual 07), and pilot as the independent variables.

Display type ($F(3,61)=102.143$, $p<.001$) was highly significant for the measure of RMS lateral path error during the entire approach (see fig. 22). Post hoc tests (using SNK with $\alpha=.05$), showed that significantly worse tracking of the lateral path occurred when using the Baseline Concept (missing data for FMS25; raw data only for Visual 07: mean=818 ft, n=5) than when using the three SVS Concepts, with which the pilots had precision pathway guidance during each task: Size A (mean=61 ft, n=19), Size X (mean=51 ft, n=22), HUD (mean=67 ft, n=27). There were no significant differences among the SVS concepts for this measure. Task, pilot, and the second order interaction of display type and task were not significant ($p>.05$) for this measure.

Display type ($F(3,65)=18.227$, $p<.001$) was highly significant for the measure of RMS vertical path error during the entire approach. Post hoc tests (using SNK with $\alpha=.05$) showed that the vertical path deviation when flying with the Baseline Concept (the pilots had differing conventional guidance information across the two tasks: mean=147 ft, n=10) was significantly worse than when flying with any of the three SVS Concepts, with which the pilots had precision pathway guidance: Size A (mean=38 ft, n=19), Size X (mean=40 ft, n=22), HUD (mean=32 ft, n=27). There were no significant differences among the SVS concepts for this measure. Task, pilot, and the interaction between display type and task were not significant ($p>.05$) for this measure.

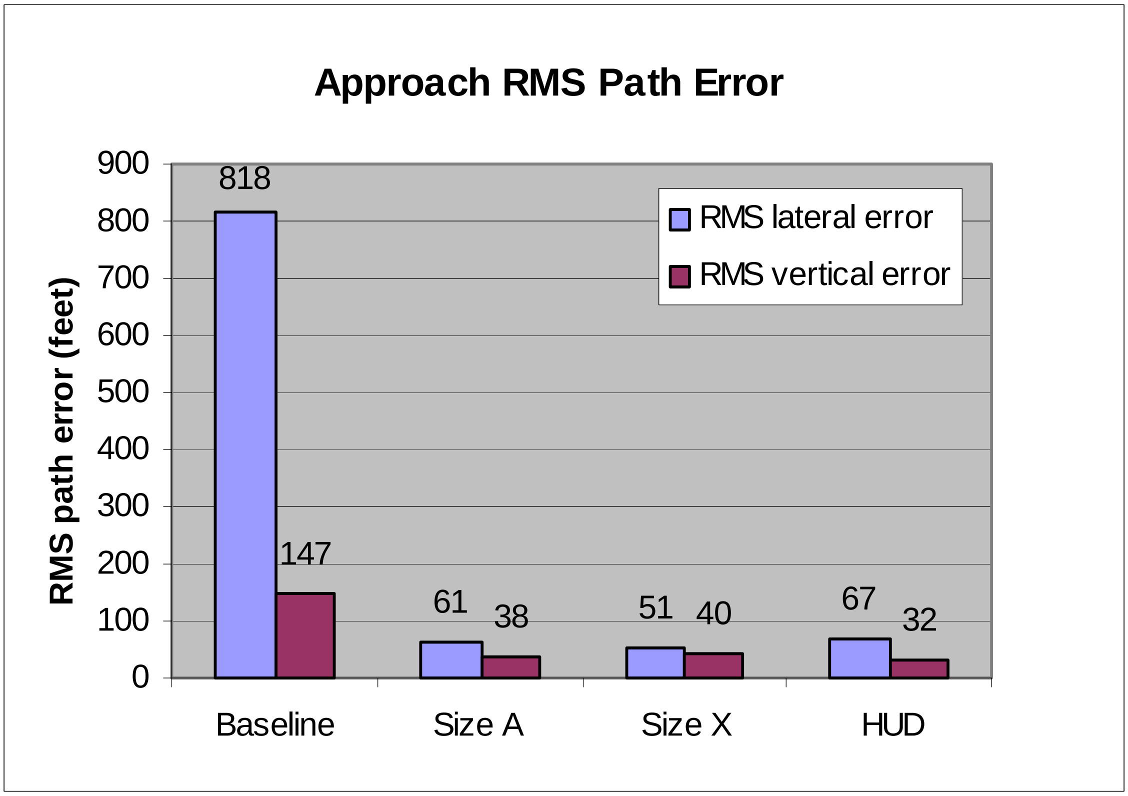


Figure 22. RMS lateral and vertical path error over the entire approach path.

SVS Display/Texture/Task Analyses. Separate ANOVAs were performed on the RMS lateral path deviation and the RMS vertical path deviation for the entire approach with SVS display type (Size A, Size X, HUD), texture type (generic, photo-realistic), task (FMS25, Visual 07), and pilot as the independent variables.

Neither the main factors nor the second order interaction between SVS display type and texture type were significant ($p>.05$) for the measure of RMS lateral path error during the entire approach. SVS display type ($F(2,56)=8.449$, $p=.001$) and task ($F(1,56)=12.884$, $p=.001$) were significant for the measure of RMS vertical path error during the entire approach. Post hoc tests (using SNK with $\alpha=.05$) showed that the vertical path deviation (fig. 22) when flying with the HUD SVS concept (mean=32 ft, n=27) was significantly better than when flying with the head-down SVS Concepts: Size A (mean=38 ft, n=19) and Size X (mean=40 ft, n=22). The pilots had worse tracking of the vertical path during the FMS25 approach (mean=39 feet) than with the Visual 07 approach (mean=34 feet). Texture type and the second order interaction between SVS display type and texture type were not significant ($p>.05$) for the measure of RMS vertical path error during the entire approach.

FMS25 approach and departure

Segment One: Inbound to Waypoint TALIA

This segment was a common path for the FMS25 and Visual 07 approaches. The pilot's task was to assume control of the airplane and maintain a straight course (no turns) while remaining level at an altitude of 13,100 feet MSL. Six runs (3 HUD, 2 Size A and 1 Baseline) were not included in these analyses due to known data contamination problems (operational restrictions, equipment problems, raster guidance symbology limitations, and cockpit distractions).

Display/Task Analyses. Separate ANOVAs were performed on the RMS lateral path deviation and the RMS vertical path deviation for Segment One with display type (Baseline, Size A, Size X, HUD), task (FMS25, Visual 07), and pilot as the independent variables.

Display type ($F(3,14)=3.743$, $p=.036$) was significant for the measure of RMS lateral path error (see fig. 23). Post hoc tests (using SNK with $\alpha=.05$) showed that significantly worse tracking of the lateral path occurred when using the Baseline concept (missing data for FMS25; raw data only for Visual 07: mean=522 ft, n=5) than when using the three SVS Concepts, with which the pilots had precision pathway guidance: Size A (mean=116 ft, n=16), Size X (mean=111 ft, n=21), HUD (mean=157 ft, n=25). There were no significant differences among the SVS concepts. Task and the second order interaction of display type and task were not significant ($p>.05$) for this measure.

Display type (see fig. 23), task, and pilot were not significant ($p>.05$) for the measure of RMS vertical path error. The second order interaction between display type and task ($F(3,39)=7.904$, $p<.001$) was highly significant for this measure. Examination of the interaction between display type and task (see fig. 24) revealed poorer vertical tracking when using the Baseline Concept for the Visual 07 task (for which the pilots had only a raw vertical path error indicator) versus for the FMS25 task (for which the pilots had flight director guidance), while the task effect for the SVS Concepts (the pilots had precision pathway guidance during each task) was diminished and in reverse order (although these differences were not statistically discriminable).

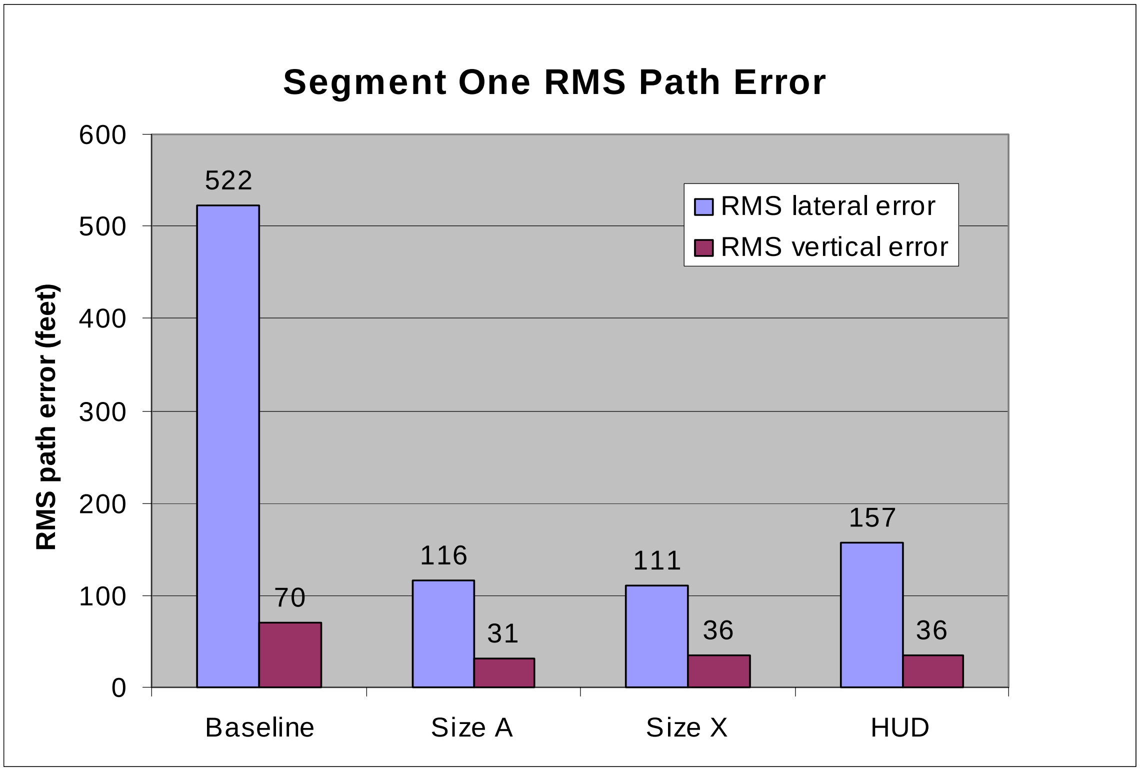


Figure 23. RMS lateral and vertical path error over segment one.

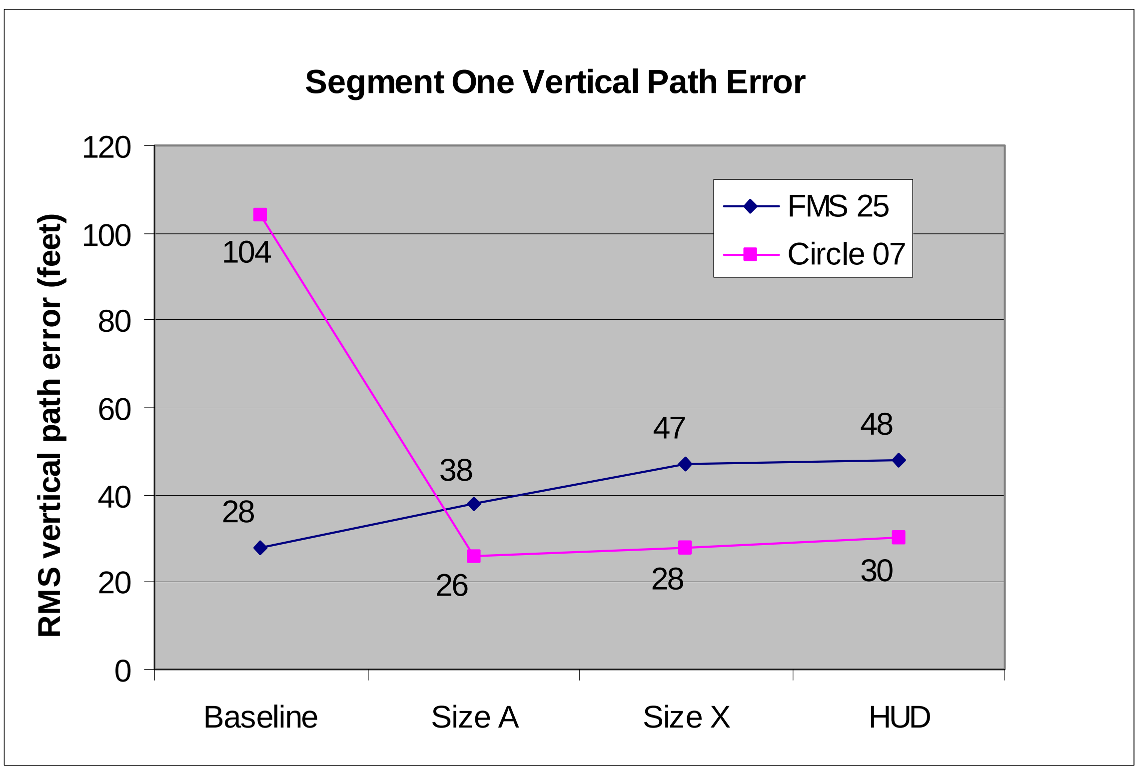


Figure 24. Second order interaction of display type and task for RMS vertical path error over segment one.

SVS Display/Texture/Task Analyses. ANOVAs were performed on the RMS lateral path deviation and the RMS vertical path deviation for Segment One with SVS display type (Size A, Size X, HUD), texture type (generic, photo-realistic), task (FMS25, Visual 07), and pilot as the independent variables. Neither the main factors nor the interaction between SVS display type and texture type were significant ($p>.05$) for the measures of RMS lateral path error and RMS vertical path error during this segment.

Segment Two: Initial Approach

This segment was a common path for the FMS25 and Visual 07 approaches. The pilot's task was to maintain a straight course (no turns), and intercept and maintain the descent path. Five runs (3 HUD, 1 Size A and 1 Baseline) were not included in these analyses due to known data contamination problems (operational restrictions, equipment problems, raster guidance symbology limitations, and cockpit distractions).

Display/Task Analyses. ANOVAs were performed on the RMS lateral path deviation, the RMS localizer error, and the RMS vertical path deviation for Segment Two, with display type (Baseline, Size A, Size X, HUD), task (FMS25, Visual 07), and pilot as the independent variables.

For Segment Two, display type ($F(3,14)=15.628$, $p<.001$) was highly significant for the measure of RMS lateral path error (see fig. 25). Post hoc tests (using SNK with $\alpha=.05$), showed that lateral path tracking performance using the Baseline concept (missing data for FMS25; raw data only for Visual 07: mean=867 ft, n=5) was significantly worse than when using the three SVS Concepts, with which the pilots had precision pathway guidance: Size A (mean=42 ft, n=19), Size X (mean=29 ft, n=22), HUD (mean=52 ft, n=27). There were no significant differences among the SVS concepts for this measure. Task, pilot, and the second order interaction between display type and task were not significant ($p>.05$) for this measure.

Display type ($F(3,15)=4.964$, $p=.014$), task ($F(1,5)=9.0$, $p=.03$), and the interaction between display type and task ($F(3,45)=15.406$, $p<.001$) were significant for the measure of RMS localizer error during Segment Two. Post hoc tests (using SNK with $\alpha=.05$) showed that the localizer tracking when using the Baseline concept (the pilots had differing conventional guidance information across the two tasks: mean=.349 dots, n=10) was significantly worse than when using the three SVS Concepts, with which the pilots had precision pathway guidance: Size A (mean=.061 dots, n=19), Size X (mean=.061 dots, n=22), HUD (mean=.064 dots, n=27). There were no significant differences among the SVS concepts. Pilots accrued less localizer error during the Visual 07 approach (mean=.097 dots) than when flying the FMS25 approach (mean=.101 dots). Although this result is statistically significant, it was not considered operationally meaningful as the difference between the two means was only .004 dots. Examination of the interaction between display type and task (see fig. 26) revealed that task differences for the Baseline were large compared to the differences for the three SVS Concepts. Larger localizer error with the Baseline display was obtained during the Visual 07 task (for which the pilots had only a raw localizer error indicator) than during the FMS25 task (for which the pilots had flight director guidance). Note that because no lateral path error data was available for the Baseline Concept for the FMS25 task (treated as missing data), a comparable statistically significant interaction was not possible for the previous analysis of the RMS lateral path error measure (lateral path error is a linear measure and as such is a more sensitive measure of path performance than the angular localizer error measure). The remaining main factor, pilot, was not significant ($p>.05$) for this measure.

Display type ($F(3,15)=8.593$, $p=.014$) was highly significant for the measure of RMS vertical path error during Segment Two (see fig. 25). Post hoc tests (using SNK with α=.05) showed that the vertical path tracking performance using the Baseline concept (the pilots had differing conventional guidance information across the two tasks: mean=185 ft, n=10) was significantly worse than the tracking performance when using the three SVS Concepts, with which the pilots had precision pathway guidance: Size A (mean=39 ft, n=19), Size X (mean=42 ft, n=22), HUD (mean=39 ft, n=27). There were no significant differences among the SVS concepts. Task, pilot, and the second order interaction between display type and task were not significant (p>.05) for this measure.

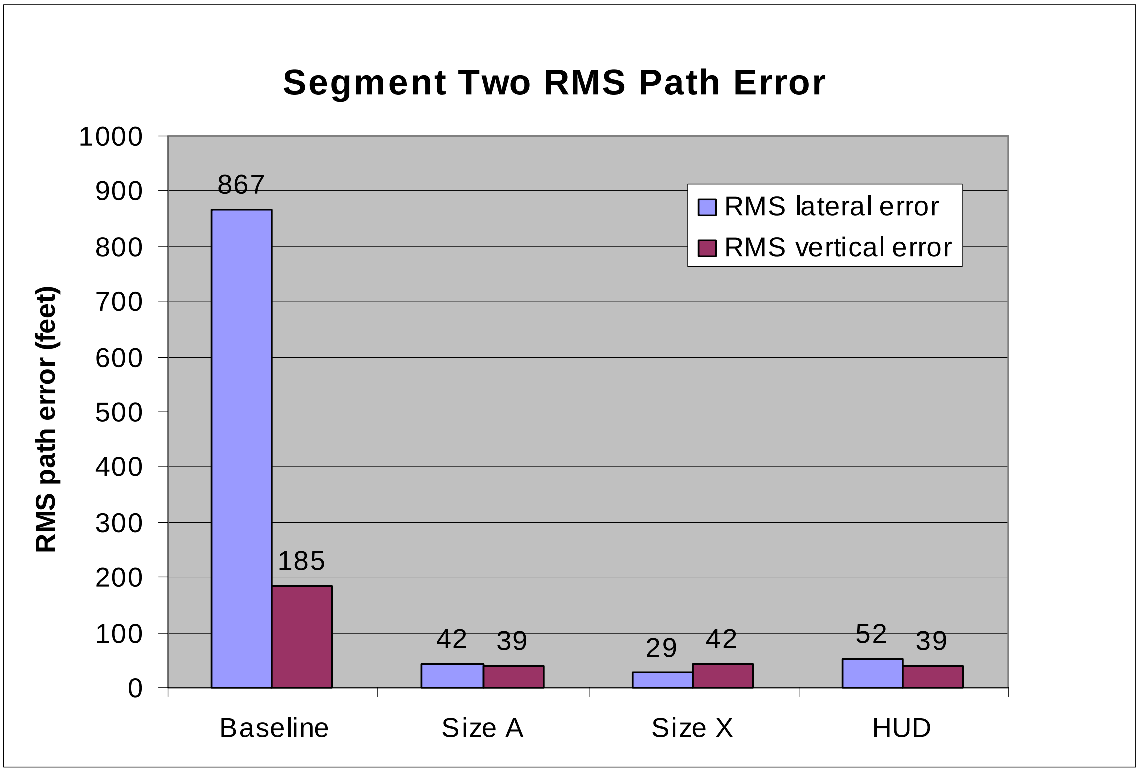


Figure 25. RMS lateral and vertical path error over segment two (initial approach).

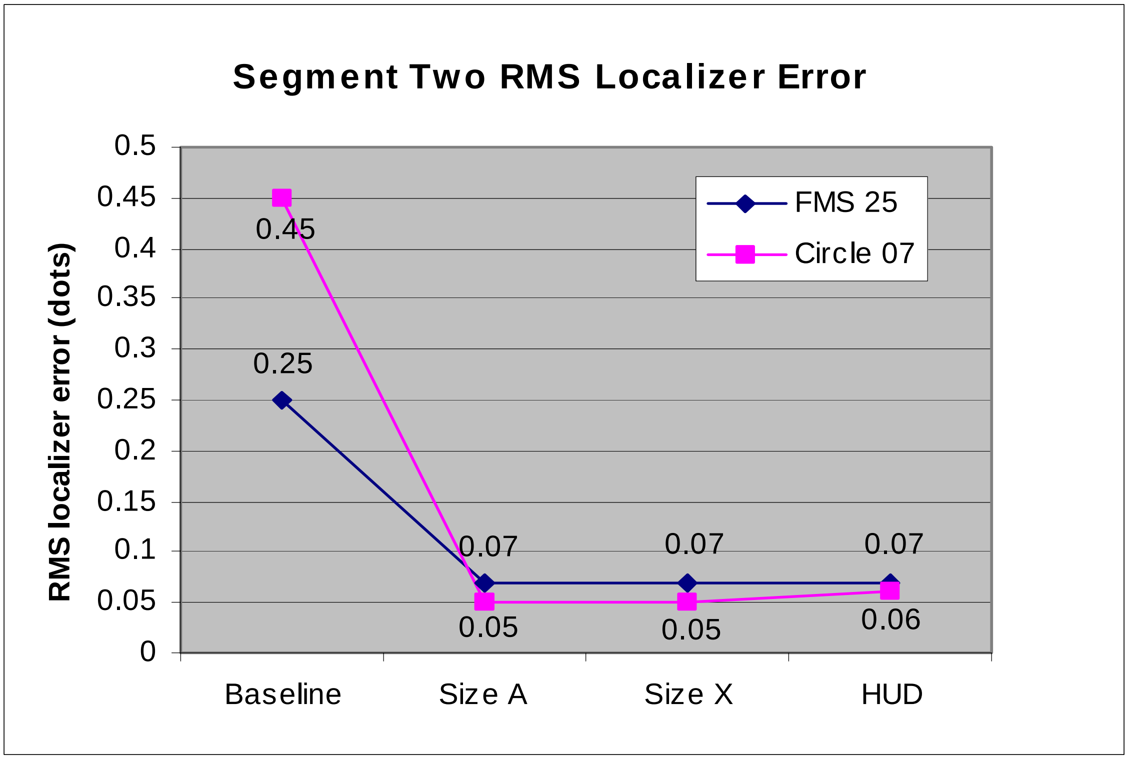


Figure 26. RMS localizer error plot of display type and task interaction over segment two.

SVS Display/Texture/Task Analyses. ANOVAs were performed on the RMS lateral path deviation, the RMS localizer deviation, and the RMS vertical path deviation for Segment Two with SVS display type (Size A, Size X, HUD), texture type (generic, photo-realistic), task (FMS25, Visual 07), and pilot as the independent variables.

Neither the main factors nor the second order interaction between display type and texture type were significant ($p>.05$) for the measure of RMS lateral path error or for the measure of RMS vertical path error. For the measure of RMS localizer, SVS display type, texture type, and the interaction between SVS display type and texture type were not significant ($p>.05$), but task was significant ($F(1,5)=3.0$, $p=.011$). Pilots accrued less localizer error during the Visual 07 approach (mean=.054 dots) than when flying the FMS25 approach (mean=.073 dots). Although this result is statistically significant, it was not considered operationally meaningful. The lateral flight plans for the Visual 07 and FMS25 over Segment Two differed by 0.02 degrees, which, at EGE's scaling of 1.5deg/dot, resulted in a 0.013 dots difference. Because of that slight path definition difference, the RMS localizer is biased by 0.013 dots between the two tasks. The statistical differences noted above (0.073-0.054=0.019 dots) are thus attributed to this path mismatch, rather than to display effects. It should be noted that the path mismatch influences on localizer error just discussed had negligible effect on the results previously presented on the Baseline condition task findings for localizer error, as the task effect was much larger and in the opposite direction there (see fig. 26: 0.25-0.45=-0.20 dots).

Segment Three: FMS25 Final Approach

This critical segment was the straight final for the FMS 25 approach. It typically ended in a takeoff/go-around (TOGA) just before the left turn away from the offset localizer course to align with the runway at 200 ft AFL. The pilot's task was to maintain a straight course (no turns) and a 3.0 degree descent path. Two runs (1 HUD and 1 Baseline) were not included in these analyses due to known data contamination problems caused by equipment problems.

Display Analyses. ANOVAs were performed on the RMS vertical path deviation and the RMS localizer error for Segment Three with display type (Baseline, Size A, Size X, HUD) and pilot as the independent variables. An ANOVA was not performed for the lateral path deviation with display type as an independent variable because there was no Baseline FMS25 data available for this measure. However, an ANOVA was performed on this measure with SVS display type as an independent variable and that analysis is presented in the next section.

Display type and pilot were not significant ($p>.05$) for the measure of RMS vertical path deviation. Display type ($F(3,11)=8.182$, $p=.004$) was highly significant for the measure of RMS localizer error (see fig. 27), an angular measure, that while less sensitive than the linear lateral path deviation measure, provides related results. Post hoc tests (using SNK with $\alpha=.05$) showed that the pilot accrued significantly more localizer error with the Baseline concept (using a conventional flight director, mean=.320 dots, n=5) than when using the three SVS Concepts (using precision pathway guidance): Size A (mean=.068 dots, n=8), Size X (mean=.070 dots, n=10), HUD (mean=.065 dots, n=11). There were no significant differences among the SVS concepts. Pilot was not significant ($p>.05$) for the measure of RMS localizer error.

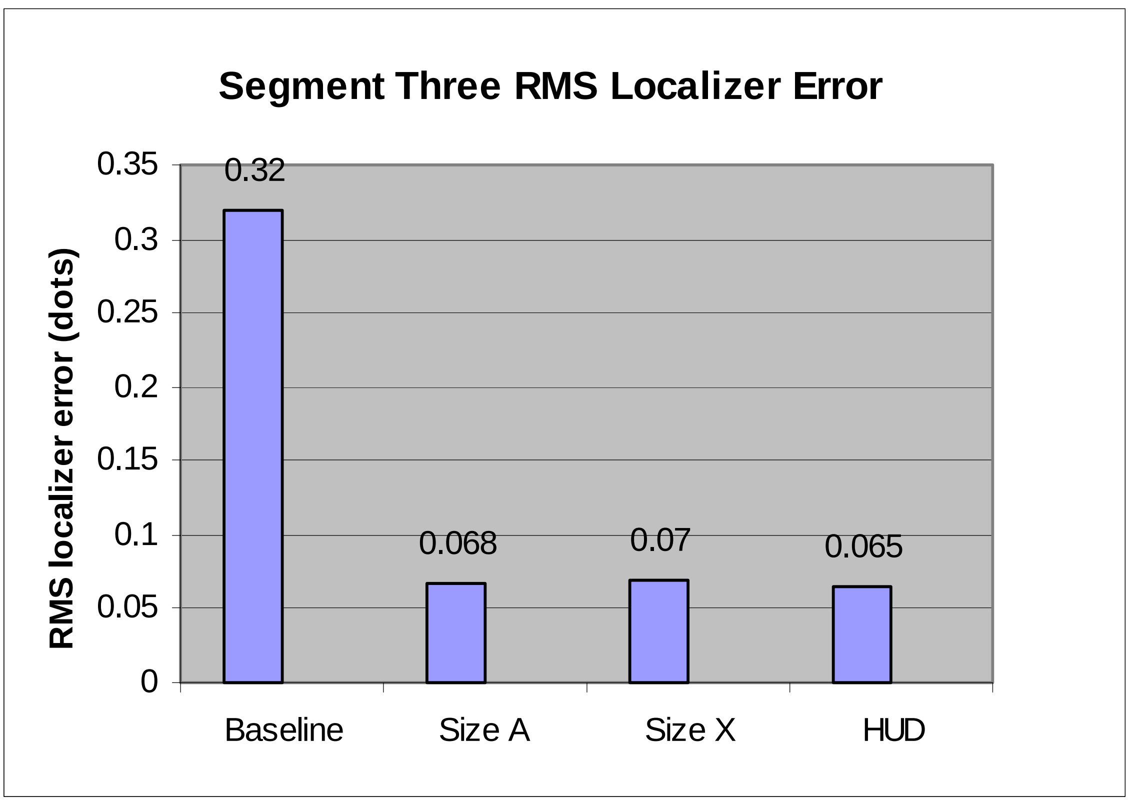


Figure 27. RMS localizer error over segment three (FMS25 short final)

SVS Display/Texture Analyses. ANOVAs were performed on the RMS lateral path deviation and the RMS vertical path deviation for Segment Three with SVS display type (Size A, Size X, HUD), texture type (generic, photo-realistic), and pilot as the independent variables.

SVS display type ($F(2,7)=11.959$, $p=.006$) was highly significant for the measure of RMS lateral path error (see fig. 28). Post hoc tests (using SNK with $\alpha=.05$), showed that the pilot had worse tracking of the lateral path with the HUD (mean=36 ft, n=11) concept than when using the other two SVS Concepts: Size A (mean=11 ft, n=8) and Size X (mean=12 ft, n=10). One could postulate that the poorer lateral tracking when using the HUD could be attributed to learning effects with the use of the vision restriction device (VRD). In general, the pilots' first HUD run was always without the VRD (all baseline runs were without the VRD and, for safety considerations, usually preceded the first HUD run to a particular runway end). Once the VRD was installed, the mean for the RMS lateral deviation when using the HUD concept (each pilot's second HUD run; mean=55 feet, n=4) increased as compared to using the HUD without the VRD installed (each pilot's first HUD run; mean=31 feet, n=4). Again, one could postulate that there was a learning effect as the pilots' tracking became better as they got used to flying with the VRD installed (each pilot's third HUD run; mean=17 feet, n=3). However, such an effect was not exhibited for the vertical error tracking when using the HUD with and without the VRD. The VRD was in place for all the Size A and X concept runs, and the Size A and X concept runs, along with texture type runs, were balanced across pilots. Conversely, turbulence effects were greater for the later runs of a sortie, such that one could argue the Size A and X concept run conditions might have been more difficult than the HUD runs. Consequently, no concrete explanation can be offered for the exceptionally good RMS lateral path tracking performance obtained over the 3.83 Nmi Segment Three when using the Size A (mean=11 ft, n=8) and Size X (mean=12 ft, n=10) concepts. Pilot, texture type and the interaction between SVS display type and texture type were not significant ($p>.05$) for the RMS lateral path error measure.

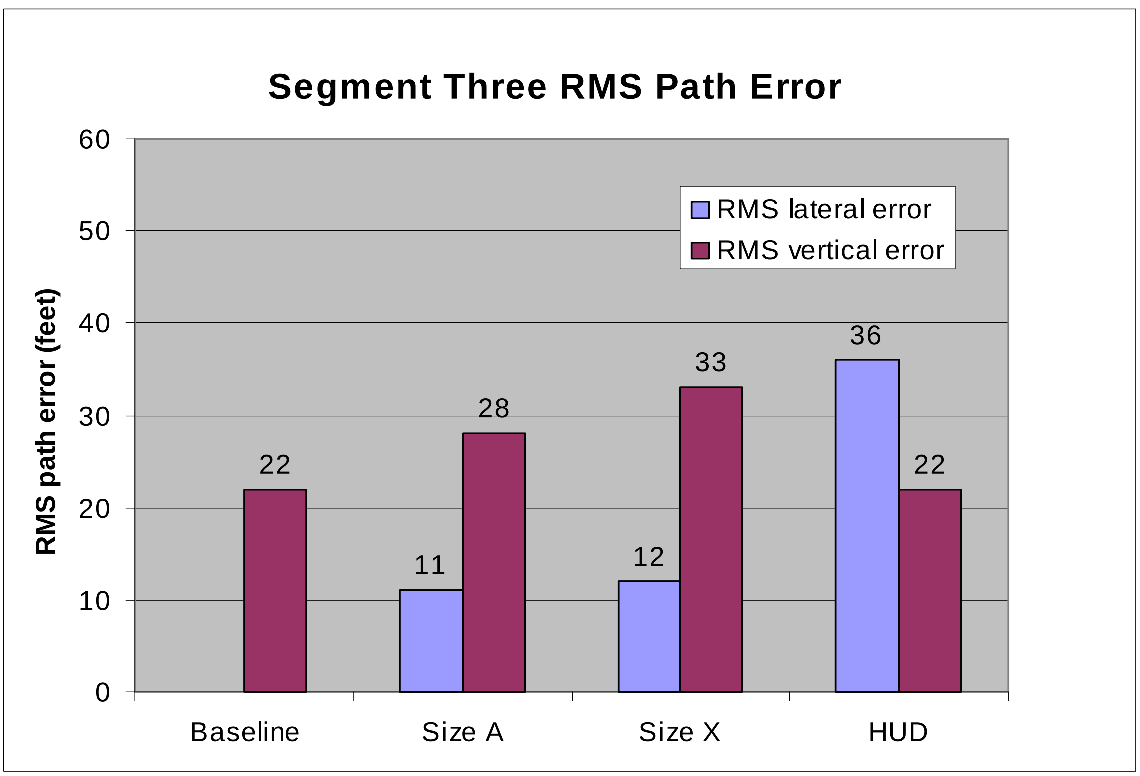


Figure 28. RMS lateral path error over segment three (FMS25 final).

SVS display type (see fig. 28), texturing type, pilot, and the interaction between texture type and SVS display type were not significant (p>.05) for the measure of RMS vertical path error during the straight final approach to Runway 25.

Segment Four: Cottonwood Departure Initial Climbout

This segment was the initial straight climbout for the Cottonwood departure of the FMS25 flying task. The pilot's task was to null the flight director. The flight director commands were based on LNAV and Speed on Pitch.

Display Analyses. ANOVAs were performed on the RMS flight director roll command and the RMS flight director pitch command with display type (Baseline, Size A, Size X, HUD) and pilot as the independent variables. Display type was not significant (p>.05) for either measure.

SVS Display/Texture Analyses. ANOVAs were performed on the RMS flight director roll command and the RMS flight director pitch command with SVS display type (Size A, Size X, HUD), texture type (generic, photo-realistic), and pilot as the independent variables. SVS display type, texture type, pilot, and the interaction between SVS display type and texture type were not significant (p>.05) for either measure.

Segment Five: Cottonwood Departure Final Climbout

This segment was the final straight climbout for the Cottonwood departure of the FMS25 flying task. The pilot's task was to null the flight director. The flight director commands were based on LNAV and Speed on Pitch.

Display Analyses. ANOVAs were performed on the RMS flight director roll command and the RMS flight director pitch command with display type (Baseline, Size A, Size X, HUD) and pilot as the independent variables. Display type was not significant (p>.05) for either measure and pilot was not significant (p>.05) for the flight director pitch command measure.

SVS Display/Texture Analyses. ANOVAs were performed on the RMS flight director roll command and the RMS flight director pitch command with SVS display type (Size A, Size X, HUD), texture type (generic, photo-realistic), and pilot as the independent variables. SVS display type, texture type, pilot, and the interaction between SVS display type and texture type were not significant (p>.05) for either measure.

Visual 07 approach

Segments one and two of this approach were covered in the section entitled FMS25 Approach and Departure, as these two segments were common to both flying tasks.

Segment Six: Circle Entry Level off

This segment was the level off before the circling approach to runway 07. The pilot's task was to level off at 8,100 ft MSL while maintaining a straight course (no turns).

Display Analyses. ANOVAs were performed on the RMS lateral path deviation and the RMS vertical path deviation for Segment Six with display type (Baseline, Size A, Size X, HUD) and pilot as the independent variables.

Display type ($F(3,14)=5.350$, $p=.012$) was highly significant for the measure of RMS lateral path error (see fig. 29). Post hoc tests (using SNK with $\alpha=.05$) showed that the pilots had worse tracking of the lateral path with the Baseline concept (for which the pilots had only a raw lateral path error indicator: mean=203 ft, n=5) than when using the three SVS concepts, with which the pilots had precision pathway guidance: HUD (mean=46 ft, n=19), Size X (mean=18 ft, n=12) and Size A (mean=28 feet, n=12) concept. There were no significant differences among the SVS concepts. The pilot factor was not significant ($p>.05$) for the RMS lateral path error measure.

Display type ($F(3,14)=12.953$, $p<.001$) was highly significant for the measure of RMS vertical path error during Segment Six (see fig. 29). Post hoc tests (using SNK with $\alpha=.05$) showed that the pilot had worse tracking of the vertical path with the Baseline concept (for which the pilots had only a raw vertical path error indicator: mean=122 ft, n=5) than when using the three SVS Concepts, with which the pilots had precision pathway guidance: Size A (mean=59 ft, n=12), Size X (mean=50 ft, n=13), HUD (mean=38 ft, n=19). Also, tracking with the HUD concept was significantly better than with the Size A concept but performance with the HUD could not be discriminated from that of the Size X concept. The Size X concept performance could also not be discriminated from that of the Size A concept. The pilot factor was not significant ($p>.05$) for the RMS vertical path error measure.

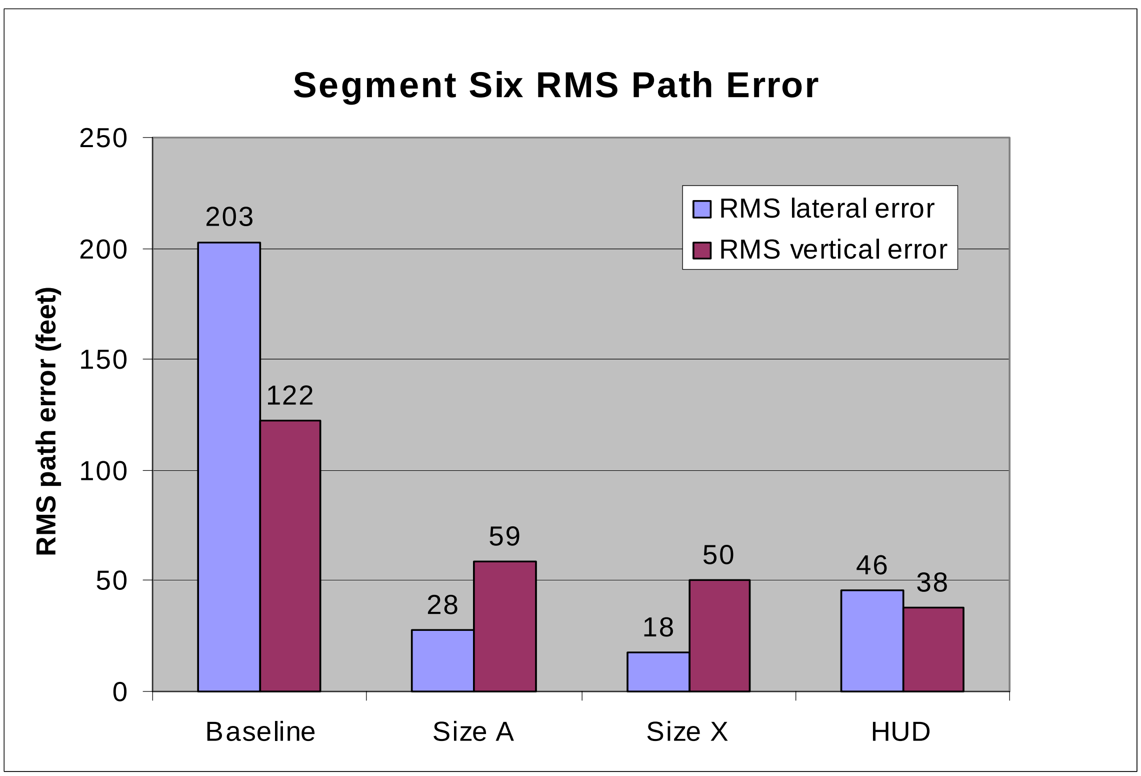


Figure 29. RMS lateral and vertical path error over segment six (circle entry level off).

SVS Display Type/Texture Analyses. ANOVAs were performed on the RMS lateral path deviation and the RMS vertical path deviation for Segment Six with SVS display type (Size A, Size X, HUD), texture type (generic, photo-realistic), and pilot as the independent variables. SVS display type

(F(2,10)=5.425, p=.025) was significant for the measure of RMS lateral path error. However, post hoc tests (using SNK with α=.05) could not discriminate between the three SVS concepts for this measure. The SNK uses a different statistical model than the ANOVA and in this case had less power to discriminate between the means. (See Display Analyses section above and fig. 29 for the means.) Texture type, pilot and the interaction between SVS display type and texture type were not significant (p>.05) for the RMS lateral path deviation measure.

SVS display type, texture type, the interaction between SVS display type and texture type, and pilot were not significant (p>.05) for the measure of RMS vertical path error.

Segment Seven: Circle Dogleg

This segment was the level dogleg left turn prior to the right circling approach to runway 07. The pilot's task was to maintain altitude while executing the turn and then to maintain a straight and level course (no turns).

Display Analyses. ANOVAs were performed on the RMS lateral path deviation and the RMS vertical path deviation for Segment Seven with display type (Baseline, Size A, Size X, HUD) and pilot as the independent variables.

Display type (F(3,14)=19.133, p<.001) was highly significant for the measure of RMS lateral path error (see fig. 30). Post hoc tests (using SNK with α=.05) showed that lateral path control using the Baseline concept (for which the pilots had only a raw lateral path error indicator: mean=522 ft, n=5) concept was significantly worse than when using the three SVS Concepts, with which the pilots had precision pathway guidance: Size A (mean=35 ft, n=12), Size X (mean=39 ft, n=12), HUD (mean=50 ft, n=19). There were no significant differences among the SVS concepts for the RMS lateral path deviation measure. The pilot factor was not significant (p>.05) for the RMS lateral path error measure.

Display type (F(3,14)=21.063, p<.001) was also highly significant for the measure of RMS vertical path error during Segment Seven (see fig. 30). Post hoc tests (using SNK with α=.05) showed that the pilots had worse tracking of the vertical path with the Baseline concept (for which the pilots had only a raw vertical path error indicator: mean=86 ft, n=5) than with any of the three SVS Concepts, with which the pilots had precision pathway guidance: Size A (mean=19 ft, n=12), Size X (mean=18 ft, n=12), HUD (mean=11 ft, n=19). There were no significant differences among the SVS concepts. The pilot factor was not significant (p>.05) for the RMS vertical path error measure.

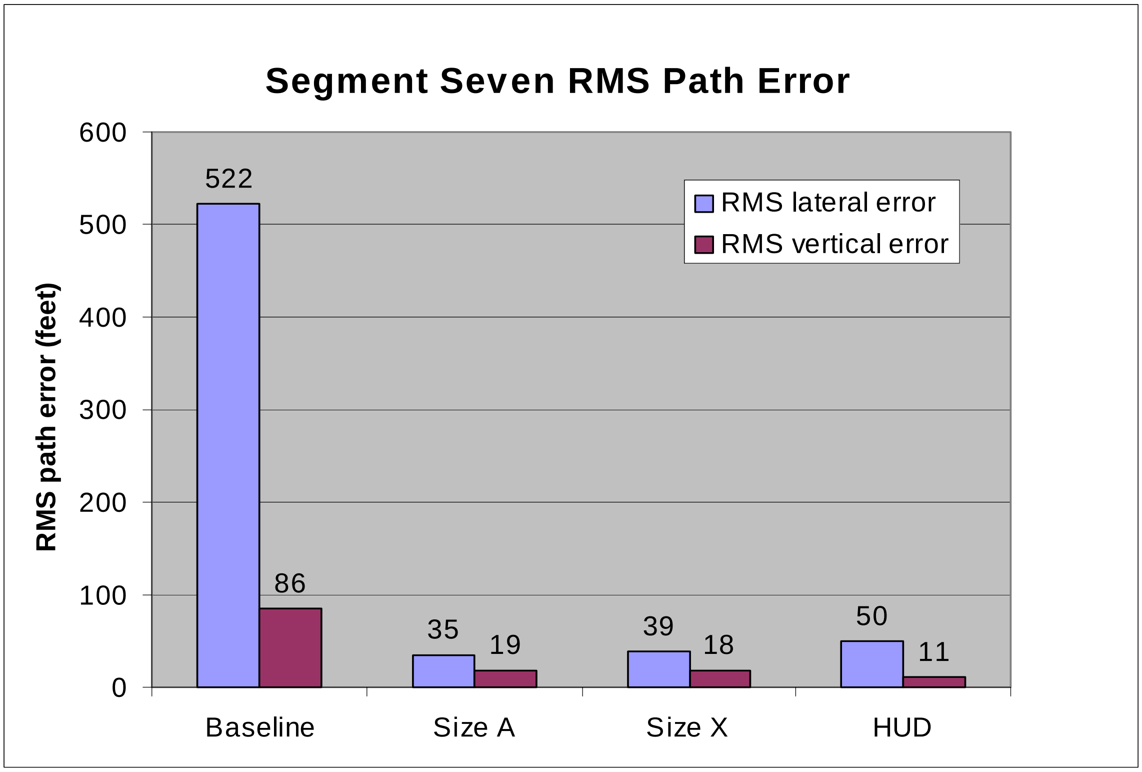


Figure 30. RMS lateral and vertical path error over segment seven (circle dogleg).

SVS Display/Texture Analyses. ANOVAs were performed on the RMS lateral path deviation and the RMS vertical path deviation for Segment Seven with SVS display type (Size A, Size X, HUD), texture type (generic, photo-realistic), and pilot as the independent variables. SVS display type, texture type, the interaction between these 2 main factors, and pilot were not significant ($p>.05$) for either measure.

Segment Eight: Circling Approach

This segment was the circling, descending approach to runway 07 with a rollout on short final at about 350 ft AFL. The pilot's task was to intercept and maintain the 3.0 degree descent path while executing the circling right turn to rollout on final. This critical segment typically ended in a TOGA just before 200 ft AFL.

Display Analyses. ANOVAs were performed on the RMS lateral path deviation and the vertical path deviation for Segment Eight with display type (Baseline, Size A, Size X, HUD) and pilot as the independent variables.

Display type ($F(3,14)=17.627$, $p<.001$) was highly significant for the measure of RMS lateral path error (see fig. 31). Post hoc tests (using SNK with $\alpha=.05$), showed that the pilot had worse tracking of the lateral path with the Baseline concept (for which the pilots had only a raw lateral path error indicator: mean=685 ft, n=5) than when using the three SVS Concepts, with which the pilots had precision pathway guidance: Size A (mean=83 ft, n=12), Size X (mean=100 ft, n=12), and HUD (mean=55 ft, n=19). Also, tracking with the HUD concept was significantly better than with the Size X concept but performance with the HUD could not be discriminated from that of the Size A concept. The Size A concept performance could also not be discriminated from that of the Size X concept. The pilot factor was not significant (p>.05) for the RMS lateral path deviation measure.

Display type (F(3,14)= 5.610, p=.010) was also highly significant for the measure of RMS vertical path error during Segment Eight (see fig. 31). Post hoc tests (using SNK with α=.05) showed that vertical path control was worse when using the Baseline concept (for which the pilots had only a raw vertical path error indicator: mean=78 ft, n=5) than when using the three SVS Concepts, with which the pilots had precision pathway guidance: Size A (mean=40 ft, n=12), Size X (mean=38 ft, n=12), and HUD (mean=20 ft, n=19). Also, tracking with the HUD concept was significantly better than with the Size A concept but performance with the HUD could not be discriminated from that of the Size X concept. The Size X concept performance could also not be discriminated from that of the Size A concept. The pilot factor was not significant (p>.05) for the RMS vertical path deviation measure.

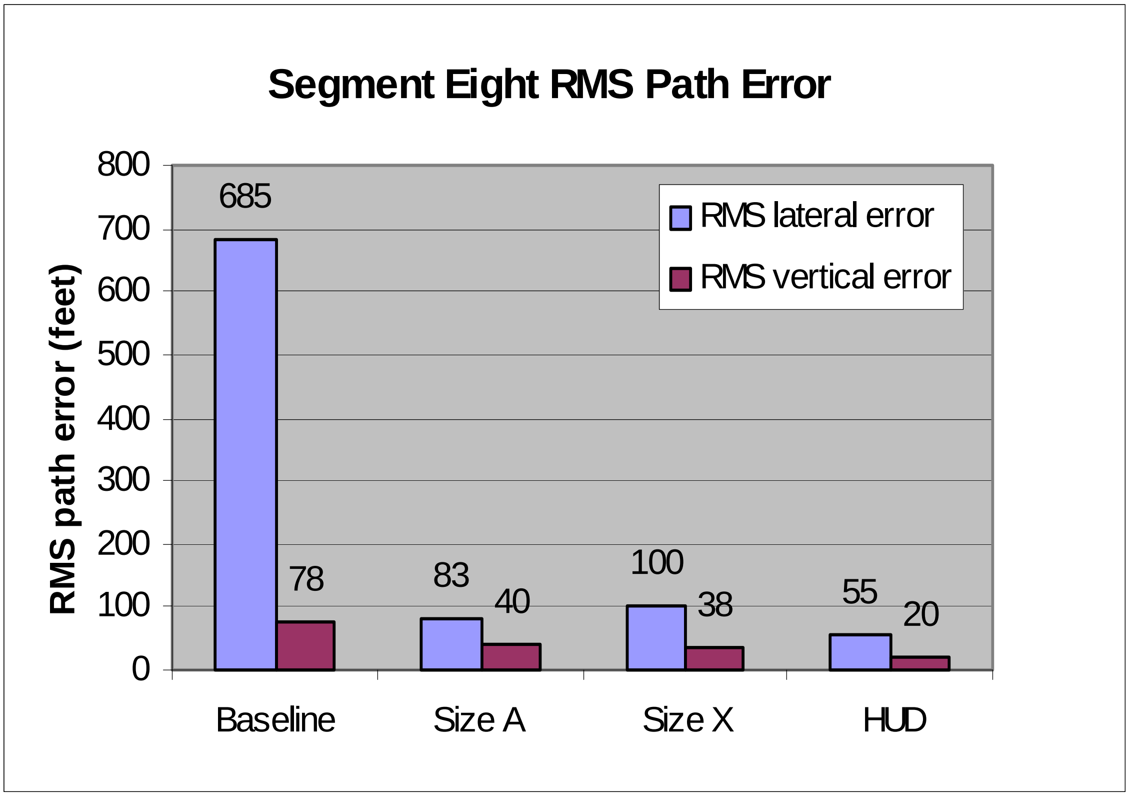


Figure 31. RMS lateral and vertical path error over segment eight (circling approach).

SVS Display Type/Texture Analyses. ANOVAs were performed on the RMS lateral path deviation and the RMS vertical path deviation for Segment Eight with SVS display type (Size A, Size X, HUD), texture type (generic, photo-realistic), and pilot as the independent variables.

The SVS-only display type analysis for the measure of RMS lateral path error is essentially a subset of the previous ANOVA treatment, but without the Baseline data and with different statistical degrees of freedom and power. Post hoc tests (using SNK with α=.05), showed that tracking with the HUD concept (mean=55 ft, n=19) was significantly better than with the Size X concept (mean=100 ft, n=12), but performance with the HUD could not be discriminated from that of the Size A concept (mean=83 ft, n=12). The Size A concept performance could also not be discriminated from that of the Size X concept. The interaction between SVS display type and texture type ($F(2,17)=3.854$, $p=.042$) was significant for the measure of RMS lateral path error. Examination of the interaction between SVS display type and texture (see fig. 32) revealed poorer lateral tracking using the Size X Photo-realistic concept than when using the Size X Generic Concept, while the texture effect for the Size A and HUD SVS Concepts was diminished and in reverse order (although not statistically discriminable). Texture type and pilot were not significant ($p>.05$) for the measure of RMS lateral path error.

SVS display type ($F(2,10)=10.139$, $p=.004$) was highly significant for the measure of RMS vertical path error. Post hoc tests (using SNK with $\alpha=.05$) showed that the pilots had better tracking of the vertical path with the HUD concept (mean=20 ft, n=19) than when using the Head-down SVS Concepts: Size A (mean=40 ft, n=12) and Size X (mean=38 ft, n=12). There were no differences among the head-down concepts for this measure. Texture type and the interaction between SVS display type and texture type were not significant ($p>.05$) for the measure of RMS vertical path error.

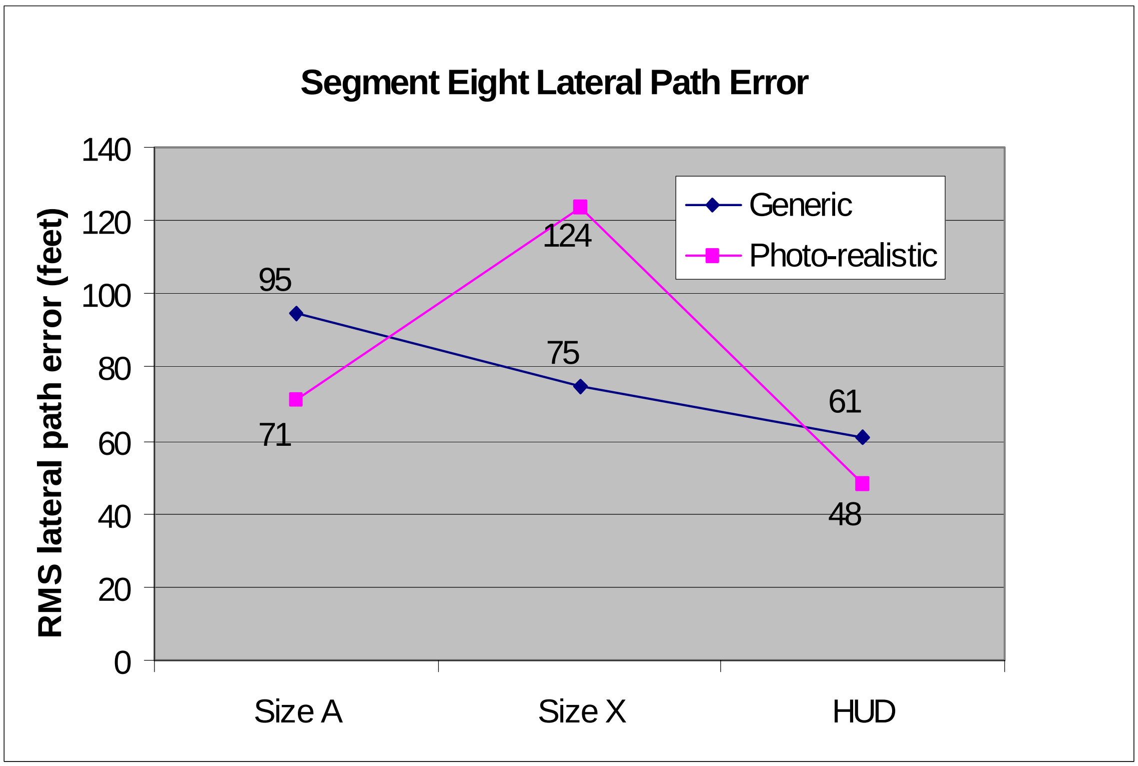


Figure 32. RMS lateral error plot of SVS display type and texture interaction.

Lateral Navigation Bin Analyses

The system performance requirements for RNAV is that each aircraft operating in RNP airspace shall have total (lateral) system error components in the cross-track and along-track directions that are less than the RNP value 95% of the flying time (see Appendix D). For the reasons cited previously in the Approach Path for FMS25 and Visual 07 section, six runs were excluded from the Lateral Navigation analyses. Figures 33-36 show the horizontal FTE distribution for the display concepts using the bin width definitions provided in table 5. The path steering error component of the RNP calculation includes both FTE and display error. For this analysis, it was assumed that display error was negligible, so FTE was the only component of path steering error. It was also assumed that the other two components (path definition error and position estimation error) of the RNP calculation would be equivalent across the display concepts evaluated.

With these assumptions, the SVS concepts yielded a horizontal FTE navigational accuracy of 0.05 nmi at least 95% of the time; while the Baseline concept was only able to yield a horizontal FTE navigational accuracy of 0.25 nmi at least 95% of the time. As such, based on the FTE distributions shown in figures 33-36, the SVS concepts with precision pathway information (Size A, Size X, HUD) would enable horizontal RNP-type operations that were five times smaller than those that would be allowed with the Baseline EADI concept.

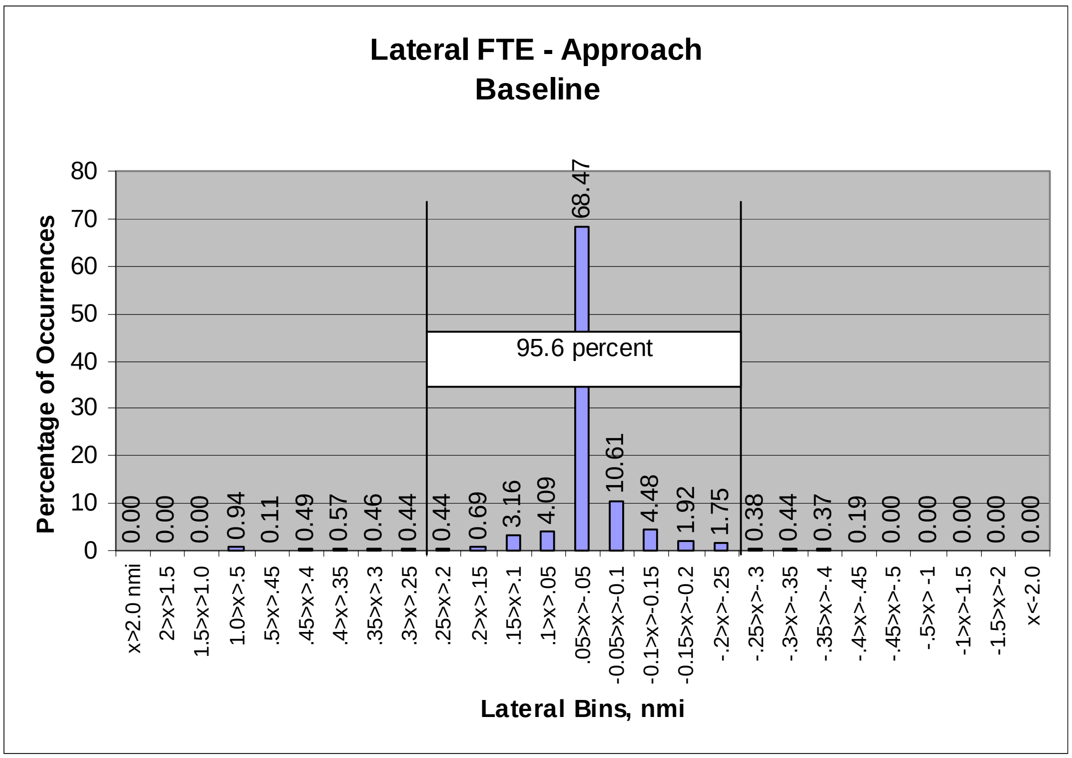


Figure 33. Lateral FTE distribution for the Baseline EADI concept

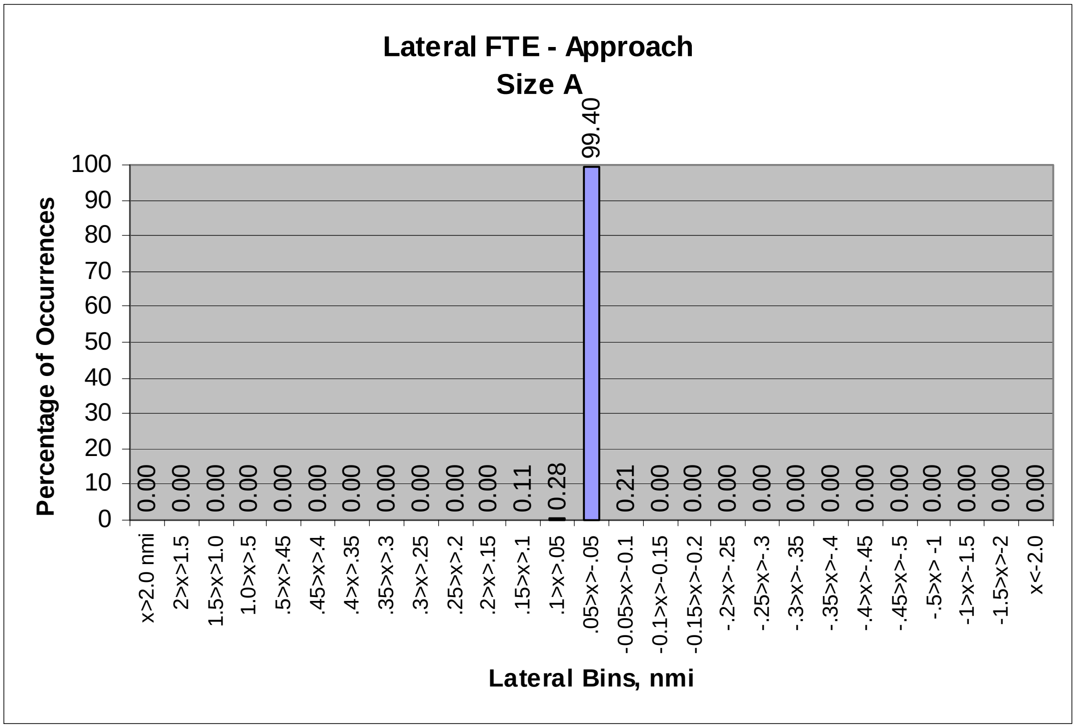


Figure 34. Lateral FTE distribution for the Size A SVS concept

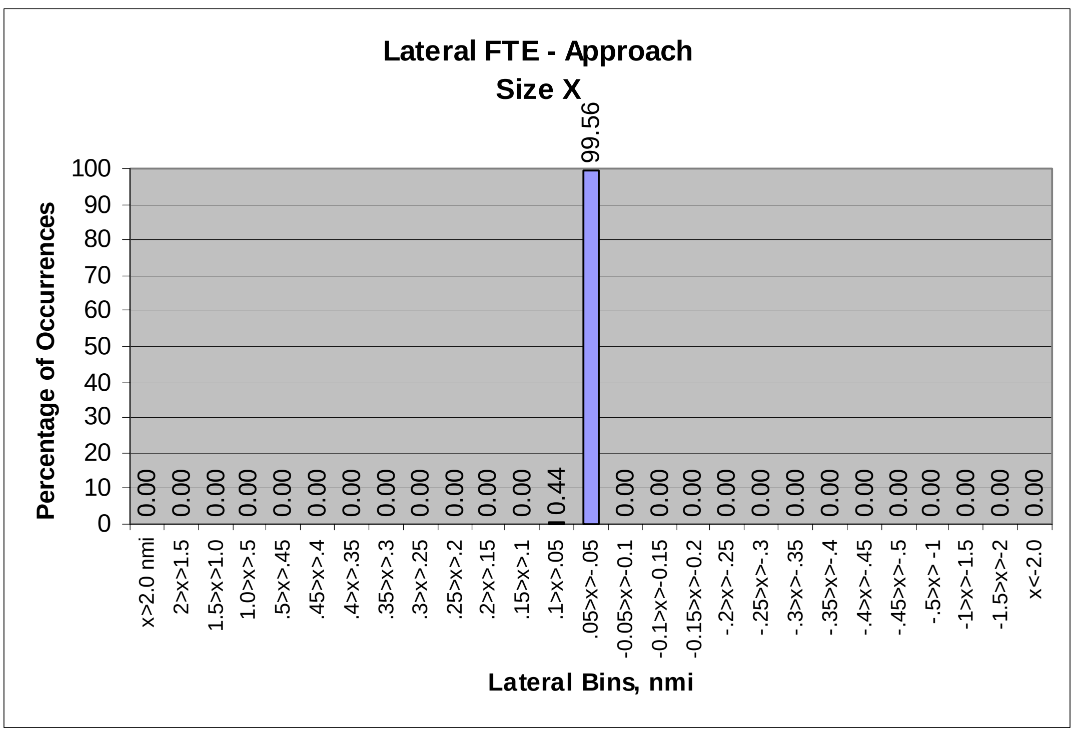


Figure 35. Lateral FTE distribution for the Size X SVS concept

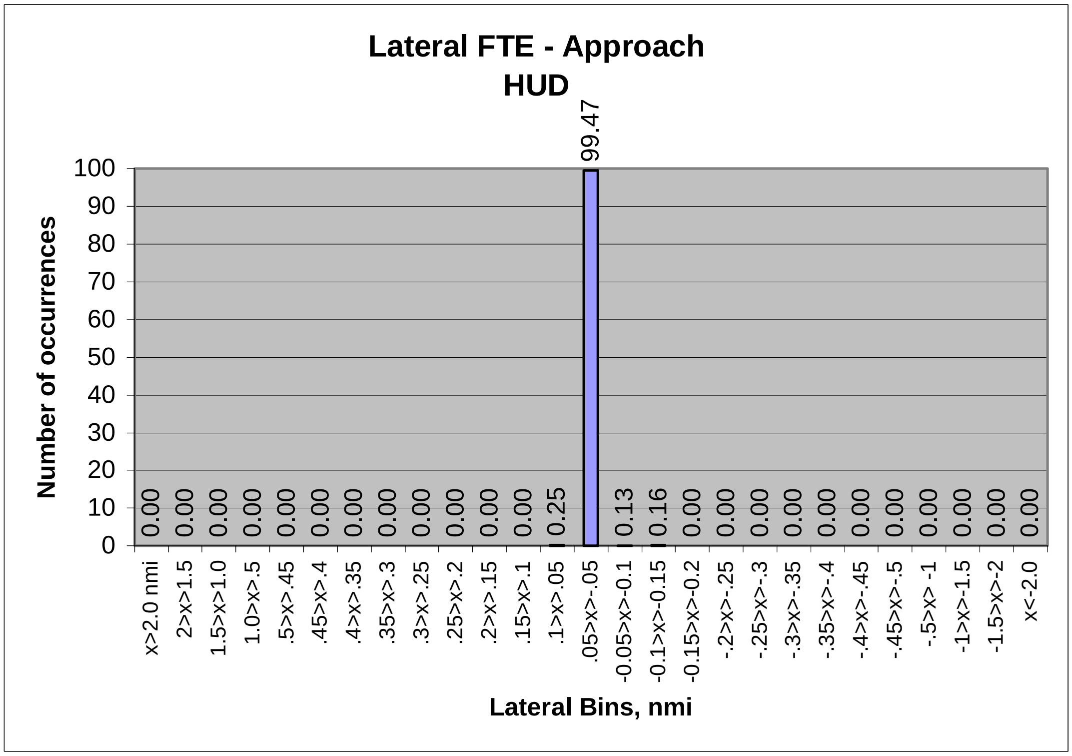


Figure 36. Lateral FTE distribution for the HUD SVS concept

Vertical Navigation Bin Analysis

The system performance requirements for VNAV are that for at least 99.7% of the time the navigational performance in the vertical plane, or the total vertical system error, is less than a specified altitude deviation measure (see Appendix D). For the reasons cited previously in the Approach Path for FMS25 and Visual 07 section, six runs were excluded from the Vertical Navigation analyses. Figures 37-40 show the vertical FTE distribution for the display concepts using the bin width definitions provided in table 6. The vertical path steering error component of the VNAV performance calculation includes both FTE and display error. For this analysis, it was assumed that display error was negligible so FTE was the only component of vertical path steering error. It was also assumed that the other three components (altimetry system error, vertical path definition error, and horizontal coupling error) of the VNAV performance calculation would be equivalent across the display concepts evaluated. In addition, it was assumed that the pilot was flying a specified vertical profile so that the required vertical navigation performance accuracy was 300 feet (see table 1).

The HDD SVS concepts (Size A, Size X) yielded a vertical FTE navigational accuracy of 150 feet at least 99.7% of the time and the HUD SVS concept yielded a vertical FTE navigational accuracy of 100 feet at least 99.7% of the time. The Baseline concept was unable to yield a vertical FTE navigational accuracy of 300 feet for at least 99.7% of the time. As such, based on the FTE distributions shown in figures 37-40, the SVS concepts with precision pathway information (Size A, Size X, HUD) would enable RNP-type operations along a specified vertical profile of 300 feet and the Baseline EADI concept would not. Thus, the SVS concepts enhance flight operations by enabling the specification of a flight path vertically for a given lateral flight path.

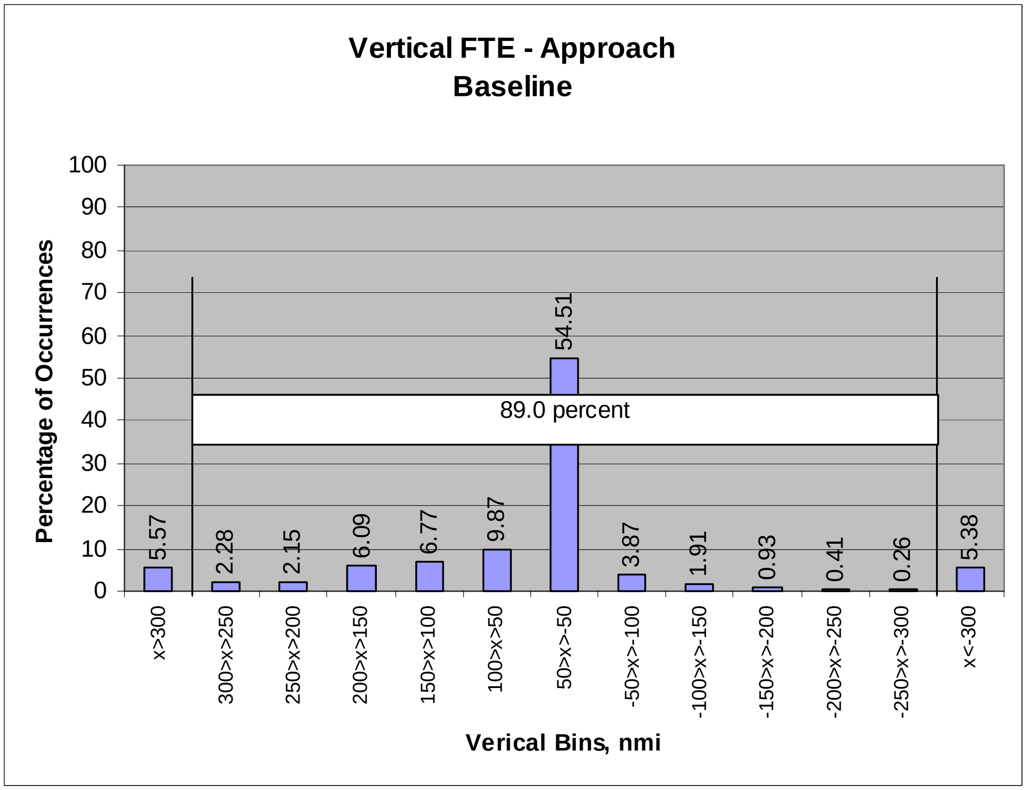


Figure 37. Vertical FTE distribution for the Baseline EADI concept

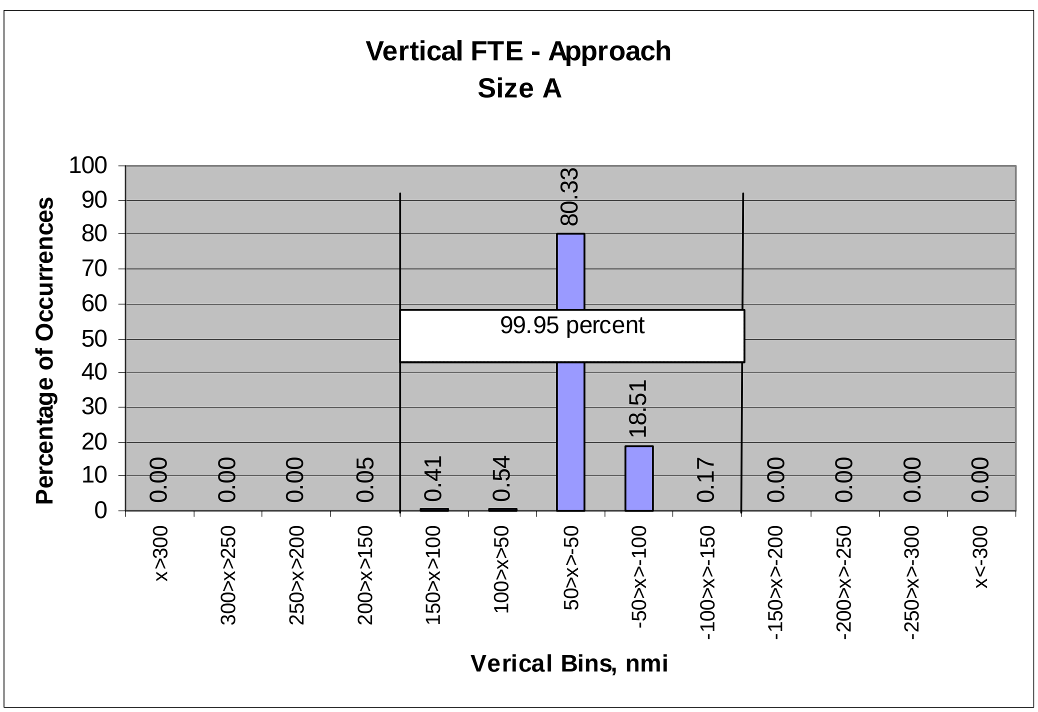


Figure 38. Vertical FTE distribution for the Size A SVS concept

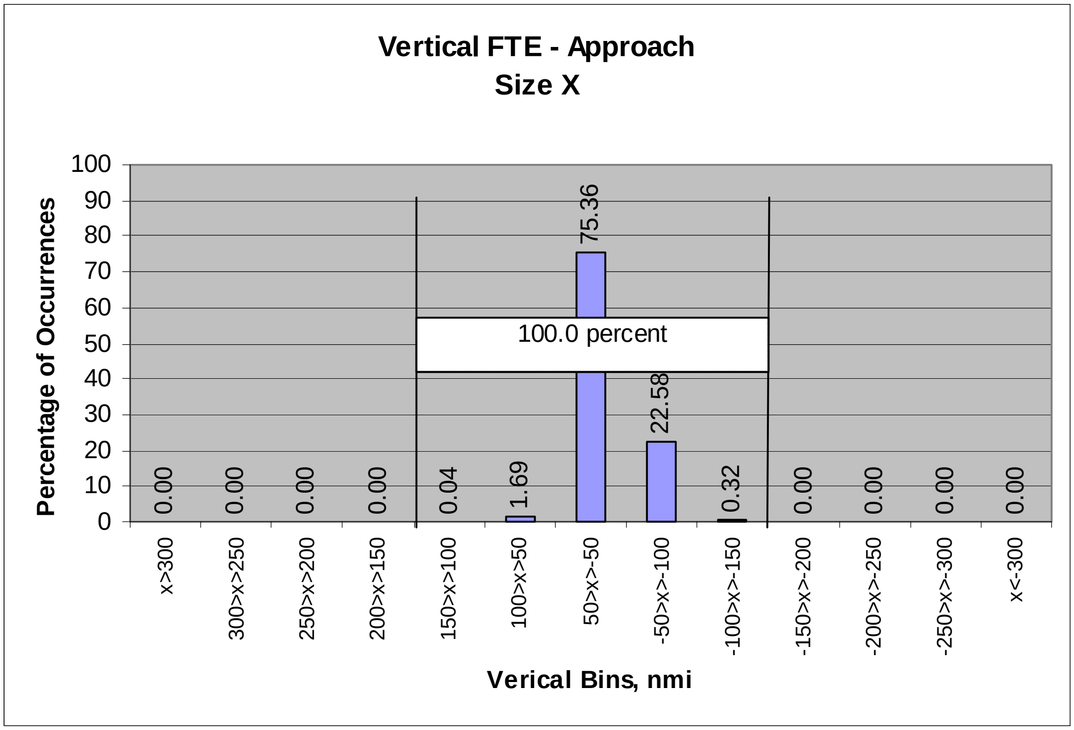


Figure 39. Vertical FTE distribution for the Size X SVS concept

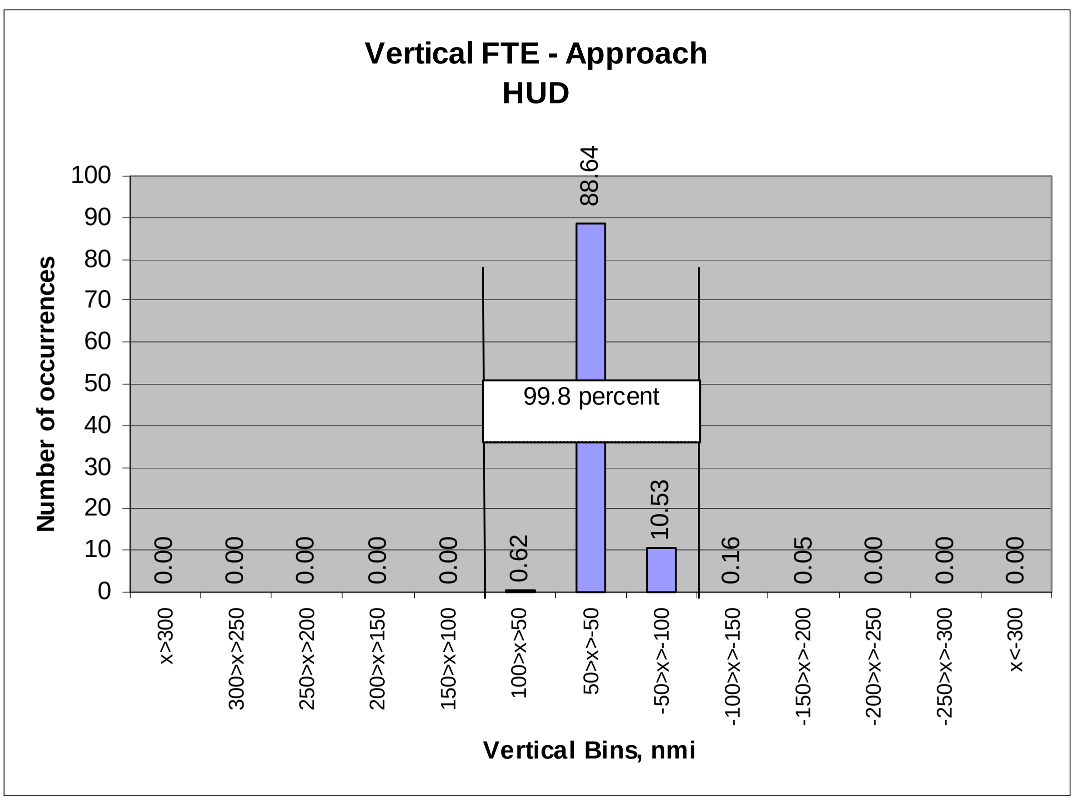


Figure 40. Vertical FTE distribution for the HUD SVS concept

Subjective Data Analyses

Post-Run Ratings

Seven post-run questions (see fig. 21) were asked of each evaluation pilot to help assess specific subjects of interest to researchers while flying the approaches with the display concepts. Only those questions of particular interest with regard to terrain awareness and pilot workload are discussed here (questions # 1, 2, and 6). An ANOVA was performed on the mean rating (1 = “strongly disagree”; 6 = “strongly agree”) for each of those post-run questions with display type (seven levels: Baseline; and Size A, Size X, and HUD, each with generic and photo-realistic terrain) and pilot as the independent variables. The pilot factor is not specifically mentioned unless it was found not to be significant.

Terrain Awareness. Post-run question # 1, “It was easy to determine aircraft position with respect to the terrain”, was asked of each EP to help assess his terrain awareness when flying the different display concepts. Display type ($F(6,73)=2.82$, $p=.016$) was highly significant for the measure of the mean terrain awareness rating (see fig. 41). Post hoc tests (using SNK with $\alpha=.05$) showed that the pilots felt that their terrain awareness while using the Size A Photo-realistic, Size X Generic, and Size X Photo-realistic concepts was significantly better than when using the Baseline EADI/TAWS ND concept. No other differences could be discriminated.

Post-run question # 2, “I was confident in the terrain information conveyed by the display”, was asked of each EP to help assess his confidence in the terrain information when flying the different display concepts. Display type ($F(6,73)=3.30$, $p=.006$) was highly significant for the measure of the mean terrain confidence rating (see fig. 41). Post hoc tests (using SNK with $\alpha=.05$) showed that the pilots felt significantly more confident in the terrain information provided by the Size X Generic and Size X Photo-realistic concepts than that of the Baseline concept. No other differences could be discriminated.

Workload. Post-run question # 6, “I could perform this task with ease and precision”, was asked of each EP to help assess his workload when flying the different display concepts. Display type ($F(6,73)=5.594$, $p<.000$) was highly significant for the measure of the mean workload rating (see fig. 41). Post hoc tests (using SNK with $\alpha=.05$), showed that use of the Baseline concept (mean=4.1) imposed significantly more workload on the pilots than the use of any of the SVS concepts: Size A Generic (mean=5.2), Size A Photo-realistic (mean=5.7), Size X Generic (mean=5.7), Size X Photo-realistic (mean=5.4), HUD Generic (mean=5.5), and HUD Photo-realistic (mean=5.7). There were no significant differences among the SVS concepts for this measure.

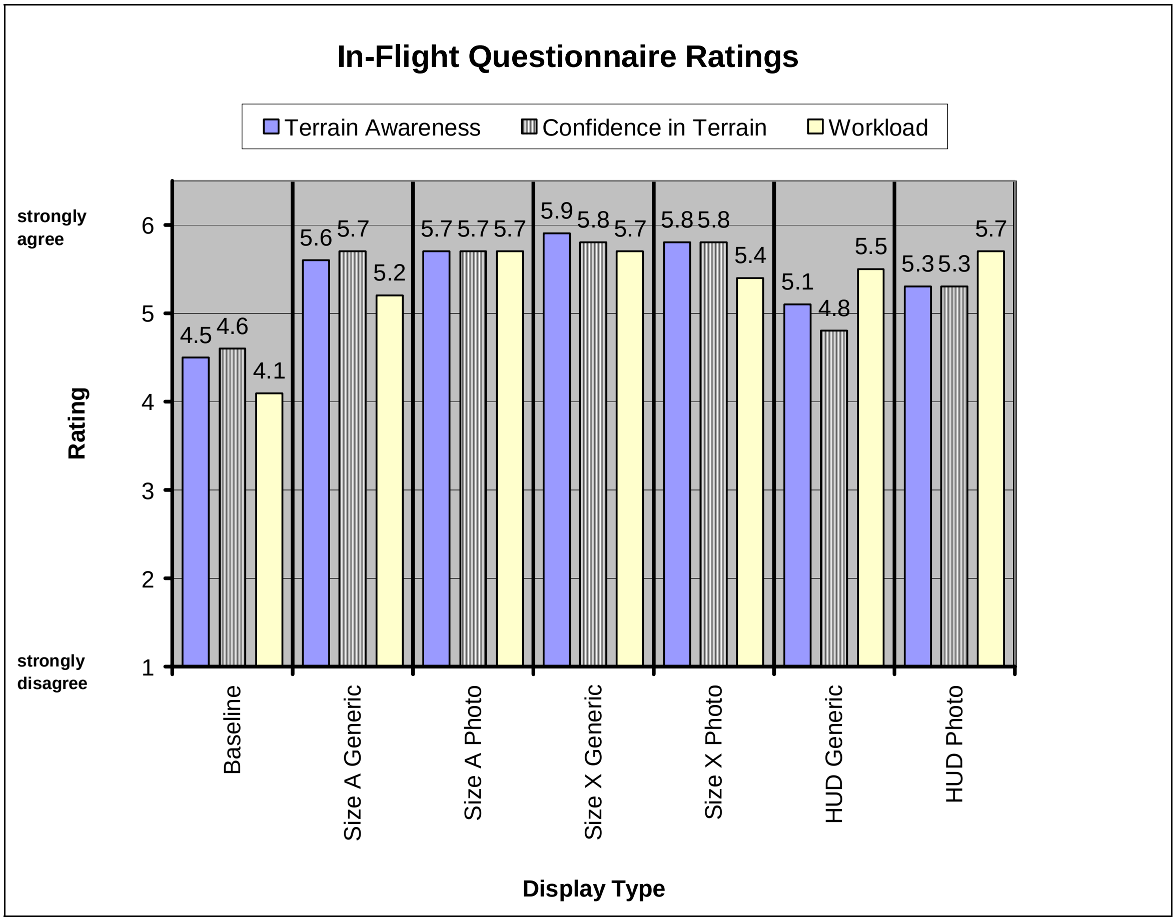
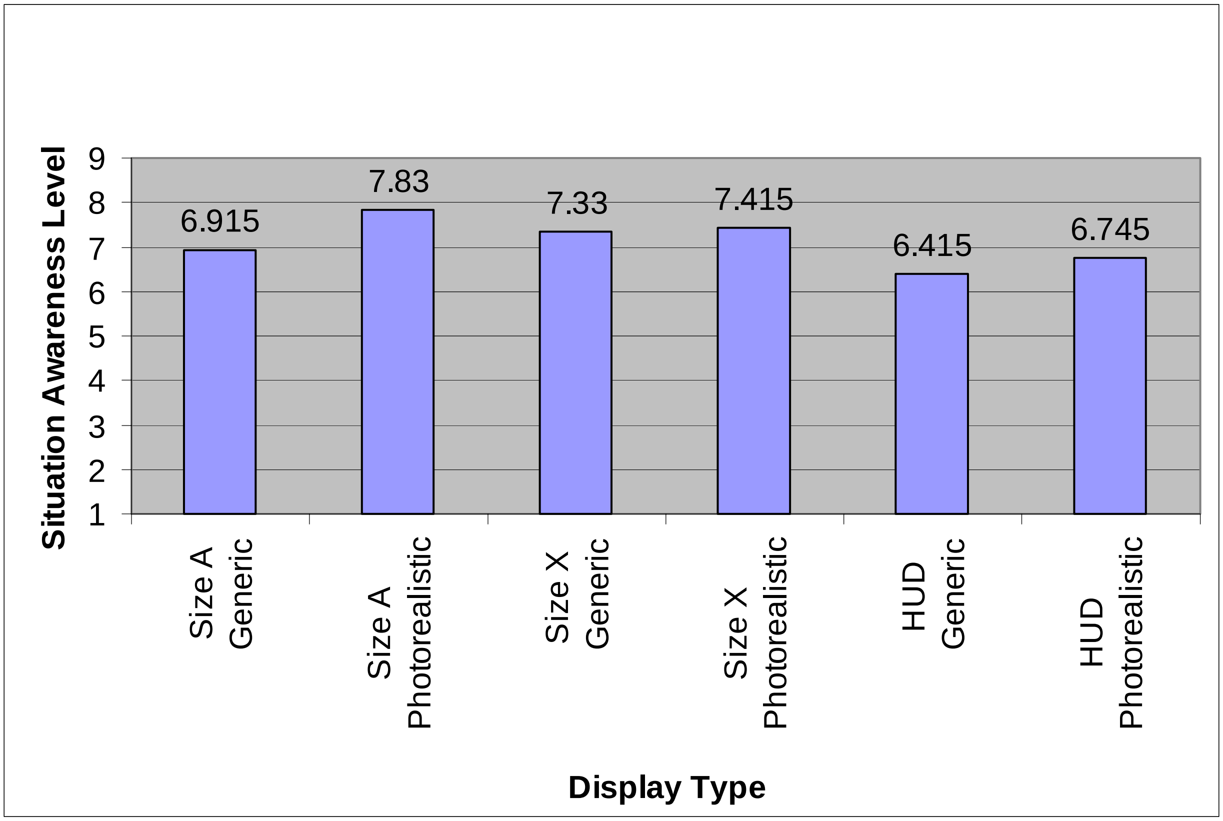


Figure 41. Post-run mean pilot ratings

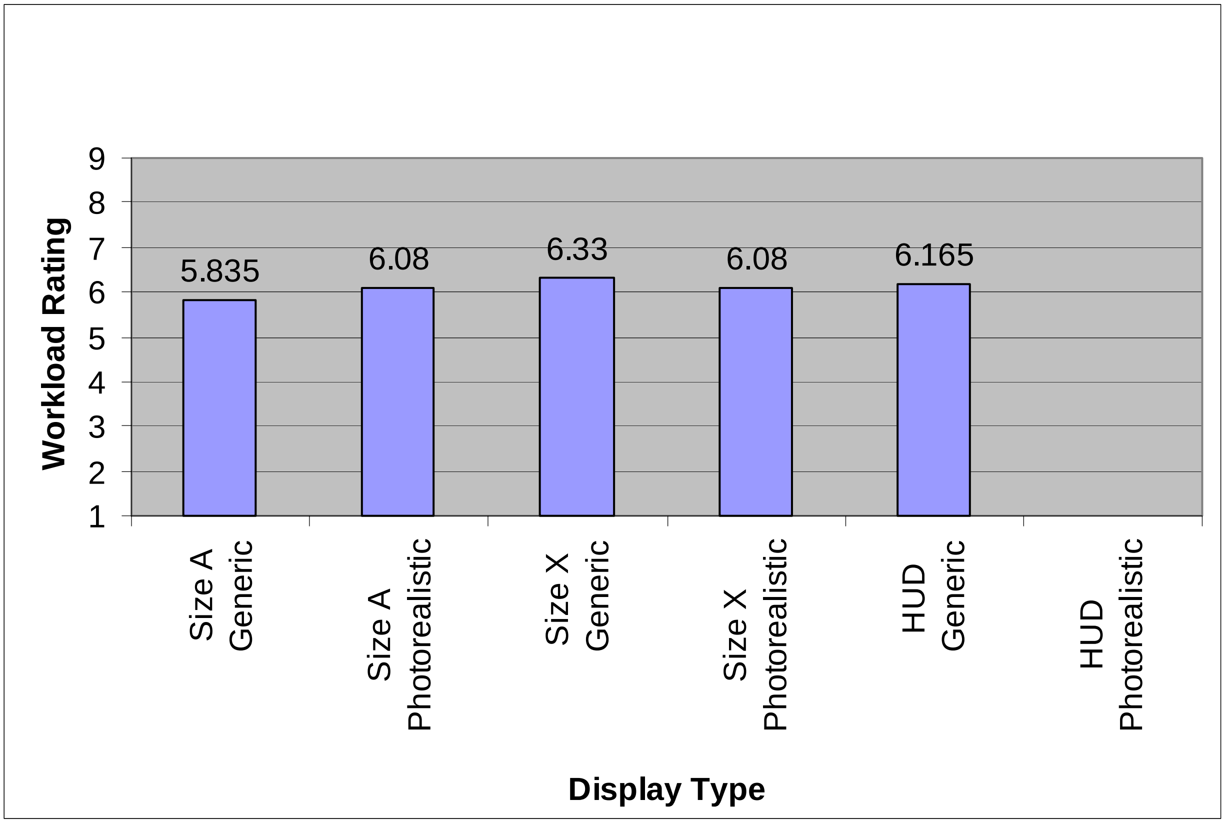
Display Questionnaire Ratings

Appendix F documents the mean and standard deviations for each of the 70 post-flight questionnaire ratings on specific subjects of interest to researchers. Those of particular interest with regard to pilot SA (questions 11-14, 43-46, and 67-70) and pilot workload (questions 8-9, 39-42, and 63-66) using SVS display concepts are presented here. Due to an omission in the questionnaire, the pilots were not asked to rate the workload for the HUD Photo-realistic concept. Mean pilot ratings of situation awareness and workload (see figures 42 and 43, respectively) for both the head-up and head-down SVS display concepts tested indicated that all of these concepts provided enhanced situation awareness while imposing low workload for the pilot. Statistical analyses of these results were not conducted.



Situation Awareness Scale								
1	2	3	4	5	6	7	8	9
Very Low		Somewhat Low			Somewhat High			Very High

Figure 42. Mean pilot situation awareness ratings versus display type



Workload Scale								
1	2	3	4	5	6	7	8	9
Very High		Somewhat High			Somewhat Low			Very Low

Figure 43. Mean pilot workload ratings versus display type

SA-SWORD Ratings

Pilots were asked to complete a paired-comparison SA-SWORD (Vidulich & Hughes, 1991). The SA-SWORD for this experiment was designed to allow a statistical analysis of the pilot's subjective assessment of the situation awareness for each of the display configurations (Baseline, Size A Generic, Size A Photo-realistic, Size X Generic, Size X Photo-realistic, HUD Generic and HUD Photo-realistic). For this exercise, SA was defined as: *The pilot's awareness and understanding of all factors that will contribute to the safe flying of their aircraft under normal and non-normal conditions.*

The responses were averaged and the overall rank order was: Size X Photo-realistic, Size X Generic, HUD Photo-realistic, Size A Photo-realistic, Size A Generic, HUD Generic, and Baseline. An ANOVA was performed on the mean rankings with display type and pilot as the independent variables. Display type ($F(6,18)=6.968$, $p<.001$) was highly significant for this measure. Post hoc tests (using SNK with $\alpha=.05$) showed that the Size X Photo-realistic had significantly higher SA-SWORD ratings than all other SVS display concepts except for Size X Generic. Three distinct, overlapping subsets (see fig. 44) were formed: 1) Size X Photo-realistic & Size X Generic; 2) Size X Generic & HUD Photo-realistic; and 3) HUD Photo-realistic, Size A Photo-realistic, Size A Generic, HUD Generic, & Baseline.

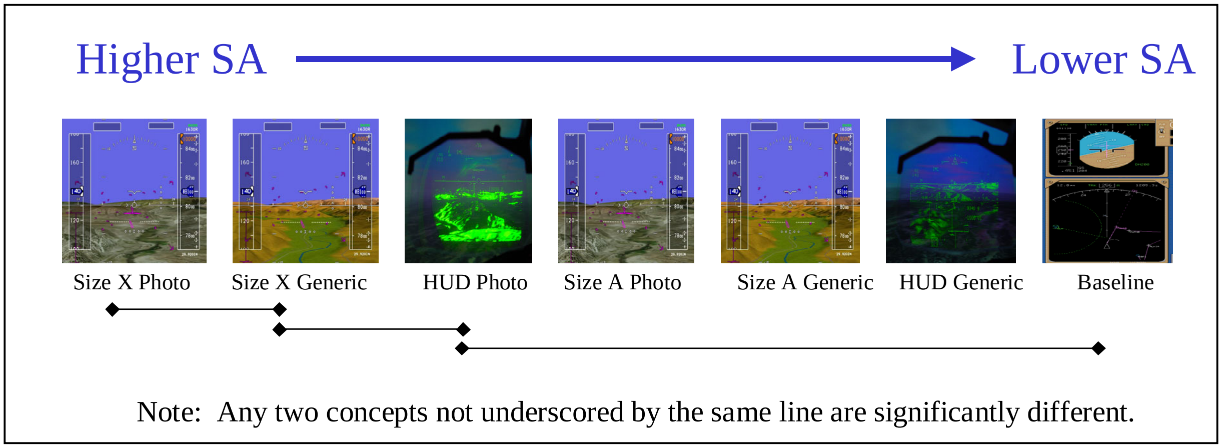


Figure 44. Comparative situation awareness among display concepts.

Pilot Comments

Video and audio recordings of each pilot were taken while they flew the two approaches and departures. In addition, each pilot's post-flight debriefing was recorded on audiotapes.

There were numerous comments on elements of the tunnel symbology but they will not be discussed here as the emphasis of this flight test was on the presentation of terrain information. In summarizing these pilot comments, the following themes emerged.

1. All but one pilot felt that the NASA SVS HUD concepts were viable for presenting terrain information to the pilot. One pilot commented that it gave a significant improvement in situation awareness over the Baseline EADI concept because of the terrain. Two of the pilots stated they would like the ability to toggle the terrain information on and off. The one differing pilot felt that a wireframe terrain HUD concept would be an improvement over the NASA HUD concepts because there are occasions when you want to see through the HUD raster image.

2. For the HDDs, all pilots overwhelming preferred the larger size display (Size X). In fact, three of the pilots commented that the Size X photo-realistic textured SVS concept provided the most enhanced situation awareness of the concepts evaluated. The pilots also stated that size (larger is better) is more important than the texturing method for the SVS concepts evaluated.

3. For the HDDs, each pilot agreed that workload, situation awareness, and pilot interpretation of performance parameters (e.g., airspeed, vertical speed information, etc.) was not affected by the type of texturing, photo-realistic or generic, employed on the SVS concept. However, four of the pilots said that they would choose photo-realistic over generic texturing for each of the HDDs evaluated.

4. Two of the pilots suggested that using both generic and photo-realistic texturing within one database would have merit as each has its advantages. Photo-realistic texturing gives a pilot an excellent view of cultural features (hills, roads, vegetation) and would be useful near the airport during approaches and departures. Generic texturing shows a pilot the angular relationship to the view of the terrain, thus enhancing the elevation cues, and would be useful when flying enroute segments.

5. Two of the pilots suggested placing waypoints with altitude information on the SVS primary flight displays. Then they could crosscheck with the Navigation Display when passing the waypoints.

Of particular interest was a comment made by one pilot after completing a Visual 07 approach with the Size A Photo-realistic concept in simulated IMC:

"I often commented to people over the years that I never ever flew a circling approach in the 141 that I was ever comfortable with, particularly at night. It always demanded a lot of attention. This was the first time I ever had an occasion of circling an approach with the kind of information I would love to have in a circling approach. Keeping me safe, I could see the terrain, taking me where I want to go, getting me all types of information in terms to where I am relative to the end of the runway. I mean it's the best of all possible worlds in terms of safety."

Discussion

The NASA AvSP SVS Project has been focused on developing new technologies that will mitigate, or even eliminate, visibility-induced accidents through the cost-effective use of synthetic vision displays. Additionally, Synthetic Vision has been forecast to reduce FTE, increase RNP capabilities, and provide other significant economic benefits. Therefore, SVS has many rewards associated with its development and implementation. To achieve such considerable potential, research is needed to deliver products which fulfill these technology objectives. Moreover, the introduction of such an innovative display concept may have unforeseen risks which requires data to safeguard the position that SVS supports “human-centered” design. Past research has consistently demonstrated that SVS is a substantial improvement over current cockpit instrumentation, and no human factors shortcomings have been uncovered. However, because one major objective of SVS is to enhance safety and operational capabilities in terrain environments, testing at a terrain-challenged location - in this case, Eagle-Vail, Colorado - was warranted.

The NASA flight test had several objectives to demonstrate the potential of SVS technology. The objectives of the research were:

a) Confirm the potential of the NASA SVS HUD concept as a retrofit solution for display of SVS concepts in non-glass cockpits. Determine the potential in both day VMC and in day, low-visibility operational environments.

b) Confirm results from piloted simulation experiments and the SVS-DFW flight test for operational utility and acceptability of various-sized (Size A, X) head-down synthetic vision displays.

c) Compare the operational utility and acceptability of photo-realistic textured with generic textured terrain databases within the NASA SVS concepts (HUD; head-down Size A, X).

d) Assess pilot path control performance (flight technical error) during manually flown landing approach and go-around maneuvers in a terrain-challenged operational environment, with and without SVS display concepts.

e) Determine required navigation performance capabilities with SVS display concepts for area navigation.

f) Confirm the situation awareness and workload benefits of SVS display concepts.

g) Provide demonstration of the economic potential of SVS for approaches that have significant restrictions for current operations.

The NASA 757 ARIES experiment was designed to achieve these objectives. Six evaluation pilots flew eighty-four flight test runs to Runway 25 and Runway 07 at the EGE airport. Each of the pilots experienced combinations of SVS display (HUD, HDD Size A, HDD Size X) and terrain texture (generic photo-realistic) configurations, and was asked to compare these display concepts to Baseline displays (i.e., EADI with TAWS/ND). Overall, the results confirm most of a priori hypotheses (the exceptions are indicated as well), and the significant findings of the flight test are discussed in the following sections.

Pilot Performance

It was hypothesized that flight technical error (in terms of RMS path performance, rather than RNP percentiles) would be lower for the SVS display concepts compared to the Baseline because of increased situation awareness and path control guidance afforded by using a flight path marker in conjunction with a pathway presentation (tunnel and guidance symbol). The significant main effects for both lateral and vertical path control showed that pilots performed the approaches with significantly lower RMS error using the SVS displays compared to the Baseline display. On average, the Baseline lateral RMS error was 818 feet and was significantly larger than the Size A (61 ft.), Size X (51 ft.) and HUD display concepts (67 ft.). A similar result was found for vertical RMS error. Post-hoc analyses confirmed that the Baseline vertical RMS error (147 ft.) was significantly larger than the SVS displays (~37 ft.). For both lateral and vertical RMS error, post-hoc analyses did not find any significant differences across the SVS display concepts. Additionally, no significant differences were found for texture type or the interaction between display size and texture type.

Analyses of RMS path performance for the individual segments, particularly for the critical final approach segments (segments 3 and 8), produced similar results. The most plausible reason for the findings are that the manually-flown approaches using the Baseline display relied on raw path error (i.e., "dogbone") indicators and in some cases a dual cue flight director (only with the FMS25 approaches), while the SVS display concepts (in addition to the raw path error indicators) had a flight path marker and a pathway presentation (tunnel and guidance symbol) that provided the pilot with additional path guidance feedback.

The pilot performance results described above confirm previous research (e.g., Comstock et al., 2001; Glaab et al., 2003) that SVS with precision guidance information can significantly reduce flight technical error. Similar results have also been reported in numerous pathway research studies (e.g., Williams, 2002) confirming the advantage of making manual approaches using a tunnel because of the added benefits of (a) tunnel or commanded display, (b) flight path marker (i.e., velocity vector), (c) 3-D perspective along the pilot's forward viewing axis, and (d) guidance (e.g., "ghost aircraft symbol"). Research has long established the benefits of prediction and preview (e.g., Lintern, Roscoe, & Sivier, 1990) and presentation of this information in a 3-D perspective (Haskell & Wickens, 1993; Parrish et al., 1994; Wickens & Prevett, 1995; Theunissen, 1997). Therefore, the finding that the SVS concepts, with tunnel information, yielded significantly improved pilot path performance compared to a Baseline concept with no tunnel was not surprising. This result suggests the use of a "pathway-in-the-sky" as a beneficial element in a synthetic vision system, and confirms the potential of these SVS concepts as retrofit candidates for replacing current displays with synthetic vision technology.

The other objective data hypotheses dealt with anticipated FTE differences between SVS display features. It was anticipated that FTE performance would be directly related to the minification factor, with better performance being achieved as minification approached unity (i.e., performance with the HUD would be better than with Size X, which would be better than with Size A). While the results tend to support those hypotheses in the majority of cases, statistical significance was rarely obtained. Certainly no meaningful differences in terms of operational significance were found. The final objective data hypothesis dealt with texture effects, and it also was not supported by the results. Either method of texturing produced equivalent FTE performance, regardless of HUD or HDD implementation. The rejection of these hypotheses is a verification of the SVS retrofit approach. That is, HUD or HDDs of any size or texture method tested were equally effective means of implementing SVS concepts to achieve FTE benefits.

Required Navigation Performance

The International Civil Aviation Organization (ICAO) Special Committee of Future Air Navigation System (FANS) developed a new concept based in terms of communication, navigation, surveillance, and air traffic management (CNS/ATM). Critical to achieving the benefits of CNS/ATM concept, aircraft will need to be able to achieve accurate, predictable, and repeatable navigation performance; this is termed RNP. Minimum Aviation System Performance Standards (MASPS) have been established for area navigation in an RNP environment, and an important objective of the EGE flight test was to establish actual navigation performance and compare it to RNP MASPS (RTCA, 2000).

It was anticipated that the increased path precision provided by the tunnel presentation would enable pilots to make manual approaches within RNP accuracies that normally require RNAV capabilities. The lateral navigation analyses confirmed that flight technical error for all the SVS display concepts achieved an accuracy of 0.05 nmi for at least 95% of the approach compared to just 0.25 nmi for the Baseline condition. The vertical navigation analyses for the head-down (Size A, Size X) and head-up SVS concepts paralleled these results in that those concepts achieved a vertical accuracy of 150 feet and 100 feet, respectively, at least 99.7% of the time which is better than the required vertical accuracy of 300 feet. Vertical path control with the Baseline EADI concept (which met required accuracy 89.0% of time) was outside RNP permissible limits. Based on these results, therefore, synthetic vision would enable manual RNP operations that are one-fifth as large for lateral RNP and within required vertical performance accuracy values than similar operations with current 757 instruments. The outcome would be an increase of RNP operations to runways that otherwise would not meet current MASPS, resulting in a significant economic advantage to airlines employing SVS technology (Hemm, 2000; Hemm et al., 2001).

Pilot Preferences

It was hypothesized that pilots would prefer all SVS display concepts over the Baseline EADI/Navigation Display, and that, between SVS display concepts, pilot preferences would be directly related to the minification factor, with preference favoring minifications approaching unity (i.e., the HUD preferred over Size X, which would be preferred over Size A). The only formal assessment of pilot preferences utilized during the flight test was the SA-SWORD, which was actually a subjective assessment of the situation awareness for each of the display configurations. That assessment, which is discussed in detail in the next section, ranked the Size X concepts ahead of the HUD and Size A concepts, with the Baseline concept ranked last. Informal pilot comments also ranked the Size X concepts as the preferred concept, and all SVS concepts were preferred over the Baseline. Thus the hypothesis concerning preference favoring minifications approaching unity must be rejected.

Situation Awareness

To achieve the national aviation objective of reducing visibility-induced accidents, perhaps the most important construct that needs to be examined with SVS is how it impacts the SA of the pilot. Therefore, several measures of situation awareness were gathered, in addition to pilot comments. Because of the nature of a flight test, there are limitations on the types of measures that may be employed. Objective measures of SA, such as SAGAT (Endsley, 1987), do not lend themselves well to the flight research environment. As a consequence, subjective measures of situation awareness were used in this flight test including the SA-SWORD pair-comparison technique (Vidulich & Hughes, 1991) and SA run questions.

After each test run, evaluation pilots were asked to complete a post-run questionnaire that included several questions about terrain awareness while flying the approaches. In general, the results suggest that the SVS display provided for greater terrain awareness than the Baseline EADI. Furthermore, the Size A photo-realistic, Size X generic, and Size X photo-realistic display concepts were rated higher in terrain awareness than the other SVS display concepts. Therefore, although synthetic vision was significantly better for pilots with regard to knowledge of terrain and aircraft position, Size A generic and the HUD concepts did not afford the same level of terrain awareness. However, during the semi-structured interview, follow-up questions about situation awareness resulted in a non-significant finding across SVS display concepts. The ratings of SA (0 to 9) ranged from 6.415 (HUD generic) to 7.83 (Size A, photo-realistic), but were not significantly different statistically from one another. Despite representing the same trend in responses as the post-run questionnaire, the post-experimental debriefings showed that all pilots felt that each of the SVS display concepts provided adequate situation awareness and, in all cases, was better than the Baseline condition.

In addition to the post-run and post-experiment questionnaires, each evaluation pilot completed the SA-SWORD that allows for paired comparison of each display concept for situation awareness. There was a significant effect found and the ranked order of the displays were: Size X Photo-realistic, Size X Generic, HUD Photo-realistic, Size A Photo-realistic, Size A Generic, HUD Generic, and Baseline. The post-hoc analyses revealed that pilots rated the Size X photo-realistic to provide greater situation awareness than all other SVS and Baseline concepts with the exception of Size X generic. Therefore, display size seems to be the primary factor determining the SA rankings, although the photo-realistic texture was consistently ranked higher within each display concept. Pilot comments would support this conclusion as many of the pilots felt that the Size X photo-realistic display concept provided the greatest situation awareness, but that Size X generic provided an almost equal degree of SA enhancement. All pilots agreed that size was more important than the texturing method although four of the pilots noted they would chose photo-realistic if given a choice. However, while most of the evaluation pilots did not discern a considerable advantage of either texture method, several pilots noted that each of the two texturing methods provided different information. For example, the photo-realistic texturing gave pilots excellent information about cultural features and was helpful for approach and departure segments. Generic texturing, on the other hand, showed pilots the angular relationship to the view of the terrain and was postulated to be useful for enroute segments. Two of the six pilots suggested that photo-realistic and generic should be combined into one database to take advantage of the benefits provided by both.

The above discussion provides the validation of all of the stated a priori hypotheses concerning the situation awareness properties associated with size and texturing methods of the SVS concepts. More importantly, the hypothesis that all SVS display concepts would be rated higher in situation awareness than the Baseline EADI/Navigation Display is clearly upheld.

Workload

Another objective of synthetic vision is to reduce mental workload of the pilot. Because SVS presents both natural and coded information to the pilot, it is postulated that it will both increase situation awareness and also reduce pilot workload by integrating often disparate pieces of information. Once again, the a priori hypotheses concerning workload included both that workload ratings would be significantly lower for all SVS display concepts compared to the Baseline EADI/Navigation Display, and that, within the SVS concepts, workload ratings would be directly related to the minification factor, with lower workload associated with minifications approaching unity (i.e., the HUD lower than Size X lower than Size A).

After each test run, evaluation pilots were asked to complete a post-run questionnaire that included a question assessing workload experienced while flying the approaches. The results were a significant main effect for display type, and pilots rated the Baseline condition to be significantly higher in mental workload compared to the SVS concepts. No significant differences were found for either display size or texture type and, therefore, pilots rated the workload equally across the SVS concepts. The post-run questionnaire results paralleled those found for the post-flight results. Thus the hypothesis concerning workload being directly related to minification factor must be rejected, while the overall SVS hypothesis is fully supported.

All pilots ranked the Baseline condition to be significantly higher in workload and lower in SA than the SVS concepts, which were all given low workload and moderate to high SA ratings. These results confirm previous research (e.g., Comstock et al., 2001; Glaab et al., 2003; Stark et al., 2001) documenting that synthetic vision has the potential to significantly reduce workload demands and, consequently, increase both the safety and efficiency of aircraft operations. In addition, these results appear to indicate that the SVS displays evaluated are approaching the goal of true human-centered design, which is high situation awareness and low workload for the pilot.

Minification Hypotheses

Prior testing at DFW had thoroughly examined pilot selectable FOV and display size effects for HDDs, finding that as range to touchdown decreased, the minification factor moved toward unity (i.e., no minification) and that as display size increased, the minification factor also moved toward unity. Combining those results with the facts that the SVS HUD concept (with unity minification) had provided equal, if not superior, pilot/vehicle tracking performance, and superior subjective ratings, compared to the HDDs, led to the postulation of the hypotheses concerning enhanced performance being directly related to minification factor (with improvements in FTE, Pilot Preference, and Workload favoring minifications approaching unity). In contrast to those results obtained in nighttime testing at DFW, where the evaluation pilots stated that they preferred the HUD to the HDD concepts, and on which the a priori hypotheses concerning enhanced performance being directly related to minification factor were based, the EGE results rejected those hypotheses (FTE, Pilot Preference, and Workload). The rejections were based on HUD ratings in daylight operations.

As at DFW, the SV-HUD concept was, for all intents, just a monochromatic green representation of the full-color, head-down display SV concept, using an RS-343 video format. No effort was expended to examine graphical light source or other terrain shading issues. In addition to the terrain presentation, the pathway guidance symbology was also presented in raster format (stroke presentation would have been preferred, but programmable stroke symbology was not available).

As a result, two significant deficiencies were encountered: illegible display renditions under some direct sunlight conditions and some reported terrain depiction illusions. These deficiencies are discussed below.

Pilot comments from the EGE flight trials indicated that there were instances where the sun angle washed out the SV HUD image and rendered the SV image unusable. To achieve the benefits of SV using the HUD, the SV raster image must be legible and useable in all foreseeable ambient background conditions. A "useable display" can be defined using many different figures of merit, but in the case of the raster HUD, contrast ratio has been specified as the figure of merit. Bailey (2002) specifies that the HUD contrast ratio requirement for a generic or photo-realistic terrain textured SVS raster HUD implementation to be on the order of 5.5. This contrast ratio value was achieved only when the ambient brightness was below 750 ft-L. In higher ambient lighting situations, the contrast ratios were less than this requirement (given the finite maximum HUD brightness capability) and some raster scene details were washed out by the ambient light.

Some pilots in the EGE flight test reported an occasional inversion illusion with the synthetic terrain HUD image, in that, at one particular point, they would interpret a valley as a ridge, and a ridge as a valley. Post-flight image evaluations and experimentation with graphic light source sun angles while generating the monochrome terrain database appeared to eliminate the problem as discussed in Bailey (2002).

These two deficiencies were not apparent at DFW, and appear to have significantly affected the EGE results for FTE, Pilot Preference, and Workload. The FTE effects are attributed to occasional loss of guidance symbology, while the subjective data effects are attributed to both deficiencies. In spite of these deficiencies, the SVS HUD concepts performed as well as the HDD concepts all of which was vastly superior to present-day cockpit display technology.

Conclusions

The NASA Synthetic Vision Eagle-Vail flight test provided a considerable amount of valuable research data that have enabled crew systems researchers to significantly improve upon SVS display concepts. The SVS Project of Aviation Safety Program is striving to eliminate poor visibility as a causal factor in aircraft accidents as well as enhance operational capabilities of all aircraft through the display of computer generated imagery derived from an onboard database of terrain, obstacle, and airport information. The goal of the flight test conducted at EGE was to extend the assessment of the SVS retrofit approach to operations in a terrain-challenged operational environment with testing in daytime conditions. EGE represented an ideal location to test the effectiveness of SVS technologies for terrain awareness and separation for approaches and departures that put the aircraft close to mountainous terrain.

All of the aforementioned flight test objectives were successfully achieved. The flight test was conducted to evaluate three SVS display types (Head-up Display, Head-Down Size A; Head-Down Size X) and two terrain texture methods (photo-realistic, generic) in comparison to the simulated Baseline Boeing-757 Electronic Attitude Direction Indicator and Navigation / Terrain Awareness and Warning System displays. These independent variables were evaluated for path error, situation awareness, and workload while making approaches to Runway 25 and 07 and during simulated engine-out Cottonwood 2 and KREMM departures. The results of the experiment showed significantly improved performance, situation awareness, and workload for SVS concepts compared to the Baseline displays and confirmed the retrofit capability of the Head-Up Display and Size A SVS concepts. The research also demonstrated that the tunnel guidance display concept used within the SVS concepts achieved RNP criteria.

Specific results of the study using objective data were:

1. FTE performance, both laterally and vertically, was significantly lower when using the SVS displays compared to the Baseline display.
2. Within the SVS concepts, FTE performance was not directly related to the minification factor, with better performance being achieved as minification approached unity (i.e., performance with the HUD would be better than with Size X, which would be better than with Size A). While the results tended to support that hypothesis in the majority of cases, statistical significance was rarely obtained. Certainly no meaningful differences in terms of operational significance were found.
3. No significant texture effects were found within the objective data. Either method of texturing produced equivalent FTE performance, regardless of HUD or HDD implementation.
4. The actual navigation performance results showed that synthetic vision (HUD or HDD) would enable manual RNP operations that are five times smaller for lateral RNP and within required vertical performance accuracy values than similar operations with current 757 instruments.

The outcome would be an increase of RNP operations to runways that otherwise would not meet current MASPS, resulting in a significant economic advantage to airlines employing SVS technology.

These objective data findings are a strong verification of the SVS retrofit approach. That is, HUD or HDDs of any size or texture method tested were an equally effective means of implementing SVS concepts to achieve FTE and RNP benefits.

Specific results of the study using subjective data were:

5. All pilots ranked the Baseline condition to be significantly higher in workload and lower in SA than the SVS concepts, which were all given low workload and moderate to high SA ratings.
6. 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 FOV techniques.
7. In contrast to the results obtained in nighttime testing at DFW, the EGE evaluation pilots stated that they preferred the HDD concepts to the HUD concept. Also the a priori hypotheses concerning enhanced performance being directly related to minification factor (with improvement favoring minifications approaching unity), which were based on the DFW results, were rejected by the EGE results. The rejections were based on HUD ratings in daylight operations. Two specific HUD deficiencies were identified, and proposed solutions to each have been presented.

These subjective data results indicate that the SVS displays evaluated are approaching the goal of true human-centered design, which is high situation awareness and low workload for the pilot.

The top-level results of the EGE flight test concerning the improved path performance, enhanced situation awareness, and lower associated workload 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.

Future Directions

The NASA Synthetic Vision Eagle-Vail flight test provided a considerable amount of valuable research data that have enabled crew systems researchers to significantly improve upon SVS display concepts. To date, several findings of the flight test have been incorporated into development of future embodiments of synthetic vision. For example, several pilots suggested that photo-realistic and generic texturing should be combined together to achieve the best that each method has to offer, and the SVS Project has developed a new hybrid texture method that meets that goal. Also, the research uncovered several issues that were unknown before research commenced. These include the usability of raster on the HUD and the presentation of the “crow’s feet” minimal tunnel symbology set that was leveraged from earlier High-Speed Civil Transport research at NASA LaRC. Several changes have been made to resolve these issues, such as development of several new tunnel concepts and modifications to the HUD to render all symbology in stroke and render the terrain in the raster channel.

Rockwell-Collins, a NASA industry partner, is employing a fish-net (grid) presentation of the terrain for their Synthetic Vision HUD concepts. The fish-net or grid presentation is a high-contrast raster image which should be legible throughout all ambient background luminance ranges since it mimics stroke-written symbology. Rockwell-Collins testing has also developed methods to ameliorate one of the past problems with fish-net type displays – the annoying and distracting bright area caused by the confluence of edgelines in valleys or vanishing points. The United States Air Force has found an Air Force pilot preference for the fish-net or grid format (Snow, 2001), especially when used in combination with an EVS image (Rate, 1984).

Direct comparisons between a fish-net and synthetic terrain HUD format were not conducted, but future NASA efforts are being directed at evaluating a fish-net terrain overlay embedded within Synthetic Vision terrain renditions. This approach is analogous to a fish-net synthetic terrain image combined with EVS. The theory is that the high contrast fish-net depiction will be noticeable and readable during all ambient lighting conditions, yet in lower ambient lighting conditions, the Synthetic Vision terrain depiction will be viewable to provide a high fidelity, unambiguous scene for terrain and obstacle awareness.

Despite the progress made to address human factors research issues, research is still needed to ensure a "human-centered" synthetic vision system. In addition to the efforts described above, crew systems researchers have been actively involved in improving upon and developing new concepts. These are part of a suite of R&D activities that form the future directions that the SVS Project is taking.

Previous flight tests of SVS have primarily focused on the general use and usefulness of SVS for providing flight critical guidance and improved situational awareness. The research objectives of these previous flight tests were focused on the SVS display (e.g., size, content, and format) and on SVS enabling technologies (e.g., Runway Incursion Prevention Systems (RIPS), Enhanced Vision Systems (EVS), and Database Integrity Monitoring Equipment (DIME)). While differential GPS and on-board databases can provide the primary framework for an operational SVS, many in the aviation community believe that independent integrity monitors for both surveillance and navigational functions will be required to meet certification and safety requirements. This functionality will rely heavily on existing on-board sensors (e.g., weather radars, high quality radar altimeters) to provide real-time integrity monitoring for the databases. Specifically, on-board integrity sensors will provide independent air-to-air, air-to-ground, ground-to-ground, and ground-to-air traffic and object surveillance, a runway incursion monitor and a confirmation of database integrity and registration (navigational position confirmation via terrain feature extraction). Additionally, the requirements for augmenting SVS concepts with the independent capabilities of weather-penetrating, enhanced vision imaging sensors during low visibility landing and surface operations conditions should be explored. These technologies form the basis for monitoring the dynamic flight environment and thereby supplement the synthetic world with real-time, direct measurement of the surrounding terrain and air/ground traffic.

A flight test evaluation is anticipated in 2004 by the NASA/LaRC under NASA's Aviation Safety, Synthetic Vision System Project to examine a synthetic vision system that integrates the enabling technologies (RIPS, EVS and DIME) of SVS. The research will focus on the integration of runway incursion prevention technologies, surface map displays, integrity monitoring, enhanced sensors, synthetic vision navigation displays, and enhanced synthetic vision primary flight and HUD displays. Together, such a synthetic vision system may considerably help meet national aeronautic goals to "reduce the fatal accident rate by a factor of 5" and to "double the capacity of the aviation system" both within 10 years (NASA, 2001).

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Appendix A. Synthetic Vision Systems Project Background

Background

In August 1996, following the wake of several commercial transport accidents that raised the level of public awareness, a White House Commission on Aviation Safety and Security was established to study matters involving these pertinent issues. The Commission's findings (Department of Transportation, 1997) concluded that although the worldwide commercial aviation major accident rate is low and has been nearly constant over the past two decades, increasing traffic over the years has resulted in an increase in the absolute number of accidents. The demand for air travel is expected to increase over the coming two decades, more than doubling by 2017. Without an improvement in the accident rate, such an increase in traffic volume would lead to a projected 50 or more major accidents a year worldwide - a near weekly occurrence. Given the very tragic, and damaging effects of a single major accident, this situation could become an unacceptable blow to the public's confidence in the aviation system. As a result, the anticipated growth of the commercial air-travel market would not reach its full potential. In February 1997, in response to the Commission's recommendations, President Clinton set a national goal to reduce the aviation fatal accident rate by 80% within ten years.

NASA Agency Role

A high priority national challenge is to ensure U.S. leadership in aviation in the face of growing air traffic volume, new safety requirements, and increasingly stringent noise and emissions standards. NASA has a successful history of leading the development of aggressive high payoff technology in high-risk areas, ensuring a proactive approach is taken to developing technology that will both be required for meeting anticipated future requirements, and for providing the technical basis to guide policy by determining feasible technical limits. Therefore, NASA created the Aviation Safety Program (AvSP) to address the President's national aviation safety goal. NASA sponsored a major program planning effort to gather input from the aviation community regarding the appropriate research to be conducted by the Agency. The NASA Aviation Safety Investment Strategy Team (ASIST) held four industry- and government-wide workshops to define and recommend research areas which would have the greatest potential impact for reducing the fatal accident rate. NASA then redirected existing research and technology efforts and formulated new ones to address the safety needs defined by ASIST (Norman, 2001).

One of the significant recommendations from ASIST was to establish a project to eliminate visibility-induced errors for all aircraft through the cost-effective use of synthetic/enhanced vision displays, worldwide terrain databases, and global positioning system (GPS) navigation. Therefore, the Associate Administrator for Aerospace Technology, Spence Armstrong, signed the Project Formulation Authorization for the Synthetic Vision Systems Project.

NASA Synthetic Vision Research Project

NASA stepped up to the challenge of eliminating visibility-induced accidents by forming the AvSP Synthetic Vision Systems (SVS) Project. Limited visibility is the single most critical factor affecting both the safety and capacity of worldwide aviation operations. In commercial aviation alone, over 30-percent of all fatal accidents worldwide (Boeing, 1996) are categorized as controlled flight into terrain (CFIT), where a mechanically sound and normally functioning airplane is inadvertently flown into the ground, water, or an obstacle, principally due to the lack of outside visual reference and situation awareness (SA). Another type of accident involving restricted visibility combined with compromised situational awareness is runway incursions. The AvSP SVS Project is developing technologies with practical applications that will eliminate low visibility conditions as a causal factor to civil aircraft accidents, as well as replicate the operational benefits of flight operations in unlimited ceiling and visibility day conditions, regardless of the actual outside weather or lighting condition. The technologies will emphasize the cost-effective use of synthetic/enhanced-vision displays; worldwide navigation, terrain, obstruction, and airport databases; and GPS-derived navigation to eliminate “visibility-induced” (lack of visibility) errors for all aircraft categories. A major thrust of the SVS Project is to develop and demonstrate affordable, certifiable display configurations which provide intuitive out-the-window terrain and obstacle information, including guidance information for precision navigation and obstacle/obstruction avoidance for commercial and business aircraft.

The ultimate goal of the SVS Project is to eliminate low visibility as a causal factor of civil aircraft accidents as recommended by the ASIST team, which would significantly help achieve national aviation safety goals. In addition, SVS may increase the efficiency of the National Airspace System by allowing precision Instrument Meteorological Conditions (IMC) operations, which presently require extensive ground infra-structure, such as Instrument Landing Systems (ILS), to many more runways than are permitted today by providing safer operations and lower weather minimums (i.e., Category I, II, IIIa, IIIb) for landing at non-ILS-equipped airports.

The SVS Project is taking the approach of employing a visual-based solution to overcome reduced pilot situation awareness caused by limited outside visibility. As a part of the SVS Project, the Synthetic Vision Display Concepts (SVDC) group focuses on SVS applications for commercial and business aircraft by designing, developing and implementing SVS display concepts for flight test and simulation evaluations and by conducting subsequent research activities. These SVS displays will provide the pilot with a clear view of the outside world through the application of sensors, such as Forward-Looking Infra-Red (FLIR), Radar, and Millimeter-Wave technologies; navigation and terrain databases; and computational subsystem components, such as image object detection and symbology generation.

Appendix B. Theoretical Foundations of Synthetic Vision Systems

It is highly unlikely that conventional display concepts can significantly increase safety as new functionality and new technology cannot simply be layered onto previous design concepts since the current system complexities are already too high (Theunissen, 1997). Better human-machine interfaces require a fundamentally new approach. One such approach applies the fundamental advantage of perspective flight path displays relative to conventional displays. 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 can now provide information about the margins within which the pilot is allowed to operate. These displays are augmented to show such information as spatial constraints and terrain constraints, rather than just showing conventional flight director commands, which only indicate an error, seemingly independent of the actual constraints. These additional display elements provide guidance that does not force the pilot to apply a continuous compensatory control strategy. Only in this way can human flexibility be exploited. This is a fundamental difference between current and synthetic vision systems (SVS) displays – that synthetic vision embodies the concept of "human-centered" design by providing natural versus coded information to the pilot (Theunissen, 1997).

Human-Centered SVS Displays. The term, "human-centered", is used to define an approach that designs to accommodate the human user in contrast to the more common "technology-centered" approach. The rapid advance of technology in the cockpit has had an unintended consequence of isolating the pilots and decreasing their situation awareness by increasing systems complexity, reducing crew-vehicle coupling, enhancing system autonomy, and reducing systems feedback (Billings, 1997). Essentially, layers of technology have removed the pilots from aircraft control, leading to the "out-of-the-loop" problem. A number of researchers have proposed a set of principles of human-centered design. Billings (1997) offered the following that are relevant to SVS:

Premise:	The pilot bears the responsibility for safety of flight
Axiom:	Pilots must remain in command of their flights
Corollaries:	Pilots must be actively involved
	Pilots must be adequately informed
	Pilots must be able to monitor the system assisting them

The use of the human-centered design perspective has important implications for the reduction of visibility-induced accidents. Past technologies have been developed with the intended purpose of prevention of several accident categories attributed to low-visibility. For example, the Ground Proximity Warning System (GPWS) was introduced in 1973 and, despite initial problems with a high false alarm rate, the 10-30 second "look ahead" capability of the system has significantly improved the situation awareness (SA) of flightcrews. However, numerous accidents, such as the A-300 Thai Airlines (1992) and B-757 American Airlines (1995) accidents, show that the GPWS is not the final solution. The introduction of the Enhanced GPWS (EGPWS) has mitigated some of the "misuse" and "disuse" (Parasuraman & Riley, 1997) issues that confront GPWS. It provides for more warning time – up to 60 seconds – and takes advantage of a worldwide digital terrain database and a color-coded display of the surrounding terrain. Ladkin (1997) asserted that there is near unanimity of the acceptance that EGPWS has improved aviation safety and reduced the incidences of controlled flight into terrain (CFIT). However, the use of technology generally follows the "warn-act" model and, therefore, requires the flightcrew to be reactive rather than proactive. The technology provides a warning when theoretically the flightcrew has already lost spatial and situation awareness and must then perform an escape maneuver. As Moroze et al. (1999) describe, the strategy may not be optimal given the reaction times required to initiate the escape maneuver and the cognitive and naturalistic decision making constraints required to adequately encode and assess the situation (i.e., situation assessment and action implementation; Parasuraman, Sheridan, & Wickens, 2000). Essentially, then, EGPWS is a "warning system" and doesn't support a human-centered design philosophy in the objective of reduction of CFIT accidents. Snow et al. (1999) declared that what is needed is an intuitive system that improves pilot situation awareness with respect to spatial orientation in terms of terrain and flight path, and does not require the pilot to divert visual attention and cognitive resources away from possible external events and primary flight reference; that is, to provide a human-centered technology that can help prevent rather than just inform the flightcrews of a potential collision with terrain. The approach requires an understanding and exploitation of the unique information processing capability of flight crews and a design of the technology and interface to accommodate perceptual and cognitive capabilities of the pilots – the difference between a "natural" and a "coded" display.

Theunissen (1997) discussed the concept of natural versus coded information. Natural information implies that the method of information acquisition by the pilot 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. Theunissen noted that it is very important to give the pilot information required to maintain SA in low-visibility conditions and that natural information presentation is intuitive and able to be perceived in a much more rapid manner than coded information. SVS displays provide a natural presentation of the outside world with information that is intuitive and easy to process.

Appendix C: Situation Awareness and Workload in Relation to Synthetic Vision Systems

Situation Awareness and SVS. There are numerous definitions of situation awareness (SA) and what it best represents. Sarter and Woods (1991) defined it as, "accessibility of a comprehensive and coherent situation representation which is continuously being updated in accordance with the results of the recurrent situation assessments." Vidulich (1994) defined SA as, "the capability to appropriately assess yourself, your system, and your environment in order to make the right decision at the right time." Endsley (1988), in contrast, stated that SA is comprised of three levels: "the perception of the elements of the environment within a volume of time and space [Level 1], the comprehension of their meaning [Level 2], and the projection of their status in the near future [Level 3]." Because there are so many definitions of what SA is, Wickens (1995) offered up a consensus definition which he proposes as: "Situation awareness is the continuous extraction of environmental information about a system or environment, the integration of the information with previous knowledge to form a coherent mental picture, and the use of that picture in directing further perception, anticipating and responding to future events." A synthetic vision system, therefore, has significant potential to improve situation awareness by fostering and developing a "picture", both figuratively and literally, of the environment and presenting that picture so that a pilot could "stay ahead" of the aircraft and maintain an accurate mental model.

Workload and SVS. Workload and situation awareness are related but are distinct psychological constructs and, therefore, have different theoretical implications for the design of a synthetic vision systems (SVS) display. Endsley (1988) noted that SA and workload could be differentiated through the effects on the pilot due to variations in task, system operation, or individual differences. She described that there are four extremes in which there is a "dissociation" between the two measures:

- low SA and low workload can arise because of inattentiveness and low motivation;
- low SA and high workload can lead to a loss of SA because the volume of information and task demands tax the ability of the pilot to keep up with the current information and properly analyze data significance;
- high SA and high workload often confronts flight crews wherein the task demands are great but the pilots work hard to manage the task situation; and
- high SA and low workload wherein flight crews are provided with the right information at the right time and in the right amount – the goal of true human-centered design and one that an SVS display as part of a human factored system could engender.

Definitions of workload are as numerous as definitions of situation awareness. Davis (1957) stated that, "paying attention to an object or an activity is regarded as imposing a measurable cost upon limited information processing resources which varies with the amount of attention paid, or the degree of 'intensive' attention. The processing of attention by the nervous system depends first upon the quality of the stimulus input, second upon the availability of mental structures to perform the mental operations necessary for processing the input, and third upon a supply of mental resources or capacity which provides the energy required for those operations to be carried out." There are a number of theories (e.g., confusion theory, single undifferentiated capacity theory, multiple resource theory) and measurement techniques (i.e., primary, secondary, physiological, and subjective) of workload.

The difference between the amount of cognitive resources available to perform a task and the difficulty of the task determines how much mental workload the pilot or flight crew experiences. Gopher et al. (1986) stated that, “Mental workload may be viewed as the difference between the capacities of the information processing system that are required for task performance to satisfy performance expectations and the capacity available at a given time.” The construct of mental workload, therefore, is partly “hardware” (e.g., channel capacity) and partly “software” (e.g., situational cognitive appraisal). Pilots are constantly confronted with new information that they have to recognize, encode, synthesize, decide upon proper course of actions to take, and then implement the action sequence to effectuate the activated decision node. Miller (1956) and information theory literature show that the channel bandwidth is limited to 5 – 9 “chunks” of information. There are considerable individual differences amongst pilots in strategies used, experiences, skills, motivations, responsiveness, and cognitive and resource management abilities. These differences can determine what constitutes a "chunk" (e.g., Miller, 1956) and whether the collective resources of the flight crew will be taxed, leading to increased mental workload. As the pilots’ capabilities to manage the task situation are exceeded, the mental workload induced can lead to performance deficits. Furthermore, research has shown that as mental workload increases, task saturation, peripheralization, tunneling, and other outcomes significantly hinder a flight crews’ ability to adequately do situation assessment, cross-checking, and hypothesis generation. Flight crews, confronted with high mental workload situations, often get “bottled in” to a single solution and fail to be able to “stay ahead of the aircraft” (i.e., Level III situation awareness; see Endsley, 1987) and perform projective management of the requirements to aviate, navigate, and communicate (Endsley, 1988; Klein, 1993; Jensen, 1995). Often, the flight crews get “led down the garden path” and get further and further behind the aircraft until they can no longer manage the task environment and understand state events, putting the aircraft into a dangerous and sometimes unrecoverable situation. SVS, therefore, could significantly mitigate a high workload situation by providing information in a natural, intuitive format that doesn’t tax the pilots in the requirement to integrate disparate pieces of flight / state data to develop and update their mental model. Presentation of precision guidance that is overlaid on a perspective, 3-D SVS display could significantly enhance situation awareness and free the cognitive resources of the flight crew to manage the non-normal or emergency events, compared to having to synthesize information from the speed and altitude tapes, flight director, terrain depiction / color codes on the navigation display, flight path and constraints, aircraft performance capabilities, Mode Control Panel settings, etc.

Appendix D: Required Navigation Performance

Required navigation performance (RNP) is a statement of the navigation performance accuracy necessary for operation within a defined airspace. RNP airspace is a generic term referring to airspace, routes, and legs, where minimum navigation performance requirements have been established and aircraft must meet or exceed that performance to fly in that airspace. The system performance requirements for RNP Area Navigation (RNAV) is that each aircraft operating in RNP airspace shall have total system error components in the cross-track and along-track directions that are less than the RNP value 95% of the flying time. RNP type is a designator according to navigational performance accuracy in the horizontal plane (lateral and longitudinal position fixing). This designator invokes all of the navigation performance requirements associated with the applicable RNP number, which is a containment value. For example, RNP-1 means that for at least 95% of the time the navigational performance in the horizontal plane, or the total horizontal system error, is less than 1.0 nautical mile (nmi). In addition to requiring 95% positioning accuracy for RNP operations, these types of procedures also require integrity of the positioning accuracy at 99.999% at 2 x RNP number. In our example above with an RNP-1, the position accuracy within 2.0 nmi of the ownship (2 x RNP value of 1.0 nmi) would have to be guaranteed to be correct 99.999% of the time to enable RNP-1 operations.

There are three lateral components of navigation error: path definition error, path steering error, and position estimation error (RTCA, 2000). These errors, defined in the following, represent the total horizontal system error of the airplane and are the difference between the aircraft's true position and desired position (see fig. D1):

- The path definition error is the difference between the defined path and the desired path at a specific point.
- The path steering error is the distance from the estimated position to the defined path. It includes both the flight technical error (FTE) and display error. FTE is the accuracy with which the aircraft is controlled as measured by the indicated aircraft position with respect to the indicated command or desired position.
- The position estimation error, also referred to as the ship's actual navigation performance (ANP), is the difference between the true position and the estimated position.

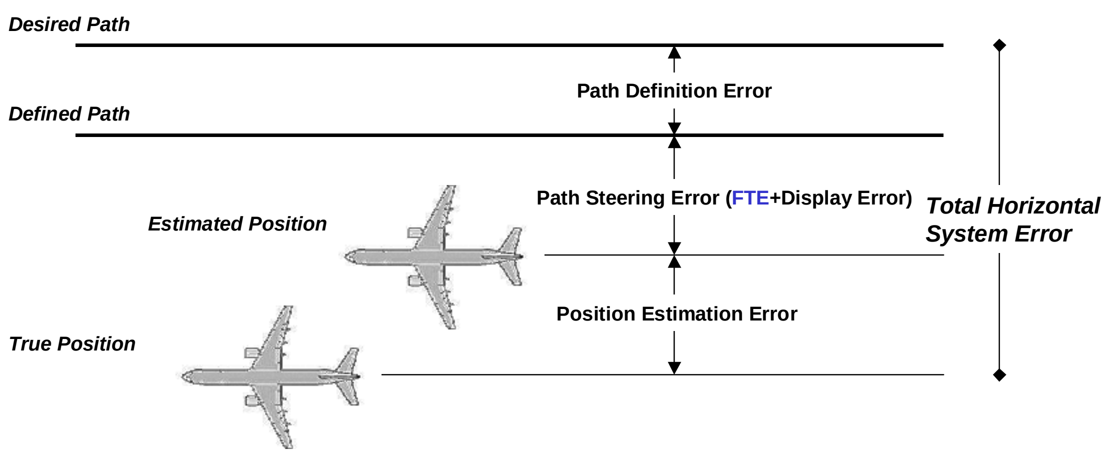

Figure D1. Lateral components of navigation error terms

Vertical navigation (VNAV) capability further enhances flight operations by enabling the specification of a flight path vertically for the lateral flight path. The system performance requirements for VNAV are that for at least 99.7% of the time the navigational performance in the vertical plane, or the total vertical system error, is less than a specified altitude deviation measure based on the airspace being flown in (below 5000 feet MSL, 5000-10000 feet MSL, above 10000 feet MSL) and the type of flight operation (level flight/climb/descent or flight along specified vertical profile) being performed (see table D1).

There are four vertical components of navigation error: altimetry system error, vertical path steering error, vertical path definition error, and horizontal coupling error (RTCA, 2000). These errors, defined in the following, represent the total vertical system error of the airplane and are the difference between the aircraft's true vertical position and desired vertical position at the true lateral position (see fig. D2):

- Altimetry system error is the error attributable to the aircraft altimetry installation, including position effects resulting from normal aircraft flight attitudes.
- The vertical path steering error is the distance from the estimated vertical position to the defined path. It includes both FTE and display error.
- The vertical path definition error is the vertical difference between the defined path and the desired path at the estimated lateral position.
- The horizontal coupling error is the vertical error resulting from horizontal along track position estimation error coupling through the desired path.

Table D1. Vertical Accuracy Performance Requirements

Error Source	Level Flight Segments and Climb/Descent Intercept of Clearance Altitudes (MSL)			Approach along Specified Vertical Profile (MSL)		
	At or Below 5000 ft	5000 ft to 10000 ft	Above 10000 ft	At or Below 5000 ft	5000 ft to 10000 ft	Above 10000 ft
Altimetry	90 ft	200 ft	250 ft	140 ft	265 ft	350 ft
RNAV Equipment	50 ft	50 ft	50 ft	100 ft	150 ft	220 ft
Flight Technical	150 ft	240 ft	240 ft	200 ft	300 ft	300 ft
Total Root-Sum-Square (RSS)	190 ft	320 ft	350 ft	265 ft	430 ft	510 ft

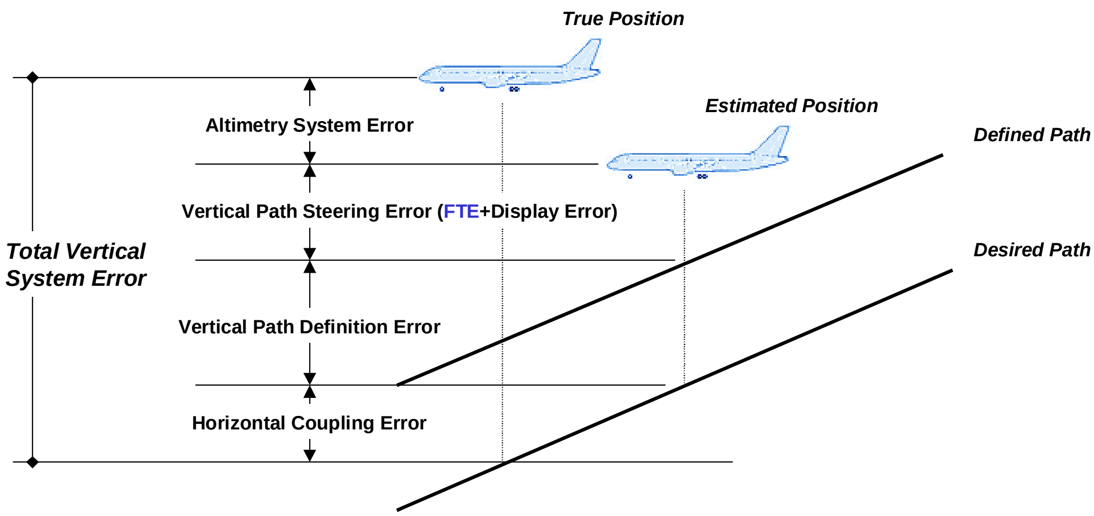

Figure D2. Vertical components of navigation error terms

Appendix E. Planned Run Matrix

The following tables show the planned run matrix / configurations by pilot for the 12 sorties (data collection flights).

Pilot #	Sortie #	Run #	Runway	Vision Restriction Device	Display Condition	Pathway
1	1	1	25	none	Baseline with flight director	none
		2	25	none	HUD, Photo-texture	yes
		3	25	yes	HUD, Photo-texture	yes
		4	25	yes	HUD, Generic-texture	yes
		5	7	none	Baseline with flight director	none
		6	7	yes	Industry Partner	yes
	2	1	25	yes	Industry Partner	yes
		2	25	yes	Size A, Generic-texture	yes
		3	25	yes	Size A, Photo-texture	yes
		4	7	yes	HUD, Photo-texture	yes
		5	7	yes	Size A, Photo-texture	yes
		6	7	yes	Size X, Generic-texture	yes
2	1	1	25	none	Baseline with flight director	none
		2	25	none	HUD, Generic-texture	yes
		3	25	yes	HUD, Generic-texture	yes
		4	25	yes	HUD, Photo-texture	yes
		5	7	none	Baseline with flight director	none
		6	7	yes	Industry Partner	yes
	2	1	25	yes	Industry Partner	yes
		2	25	yes	Size A, Photo-texture	yes
		3	25	yes	Size A, Generic-texture	yes
		4	7	yes	HUD, Photo-texture	yes
		5	7	yes	Size X, Photo-texture	yes
		6	7	yes	Size A, Generic-texture	yes
3	1	1	25	none	Baseline with flight director	none
		2	25	none	HUD, Photo-texture	yes
		3	25	yes	HUD, Photo-texture	yes
		4	25	yes	HUD, Generic-texture	yes
		5	7	none	Baseline with flight director	none
		6	7	yes	Industry Partner	yes
	2	1	25	yes	Industry Partner	yes
		2	25	yes	Size X, Generic-texture	yes
		3	25	yes	Size X, Photo-texture	yes
		4	7	yes	HUD, Generic-texture	yes
		5	7	yes	Size A, Generic-texture	yes
		6	7	yes	Size X, Photo-texture	yes

Pilot #	Sortie #	Run #	Runway	Vision Restriction Device	Display Condition	Pathway
4	1	1	25	none	Baseline with flight director	none
		2	25	none	HUD, Generic-texture	yes
		3	25	yes	HUD, Generic-texture	yes
		4	25	yes	HUD, Photo-texture	yes
		5	7	none	Baseline with flight director	none
		6	7	yes	Industry Partner	yes
	2	1	25	yes	Industry Partner	yes
		2	25	yes	Size X, Photo-texture	yes
		3	25	yes	Size X, Generic-texture	yes
		4	7	yes	HUD, Generic-texture	yes
		5	7	yes	Size X, Generic-texture	yes
		6	7	yes	Size A, Photo-texture	yes
5	1	1	25	none	Baseline with flight director	none
		2	25	none	HUD, Photo-texture	yes
		3	25	yes	HUD, Photo-texture	yes
		4	25	yes	HUD, Generic-texture	yes
		5	7	none	Baseline with flight director	none
		6	7	yes	Industry Partner	yes
	2	1	25	yes	Industry Partner	yes
		2	25	yes	Size A, Photo-texture	yes
		3	25	yes	Size A, Generic-texture	yes
		4	7	yes	HUD, Photo-texture	yes
		5	7	yes	Size A, Generic-texture	yes
		6	7	yes	Size X, Photo-texture	yes
6	1	1	25	none	Baseline with flight director	none
		2	25	none	HUD, Generic-texture	yes
		3	25	yes	HUD, Generic-texture	yes
		4	25	yes	HUD, Photo-texture	yes
		5	7	none	Baseline with flight director	none
		6	7	yes	Industry Partner	yes
	2	1	25	yes	Industry Partner	yes
		2	25	yes	Size X, Generic-texture	yes
		3	25	yes	Size X, Photo-texture	yes
		4	7	yes	HUD, Generic-texture	yes
		5	7	yes	Size X, Generic-texture	yes
		6	7	yes	Size A, Photo-texture	yes

Appendix F. Post-Flight Questionnaire Ratings

In the text below, the symbol, χ, represents the mean and the symbol, σ, represents one standard deviation. These two symbols are highlighted, italicized, and in bold font, for each question that was analyzed and presented in the Results/Subjective Data Analyses section of this paper.

Baseline EADI w/ flight director

1. Please rate the ease of performing the approach to rwy. 25 using the traditional EADI with flight director

EASE OF USE TO RWY. 25 USING EADI								
1	2	3	4	5	6	7	8	9
Very Hard		Somewhat Hard			Somewhat Easy		Very Easy	

Pilot 1: 5
Pilot 2: 7
Pilot 3: 9

Pilot 4: 3
Pilot 5: 7
Pilot 6: 6

χ = 6.16
σ = 2.04

2. Please rate the ease of performing the approach to rwy. 7 using the traditional EADI with flight director

EASE OF USE TO RWY. 7 USING EADI								
1	2	3	4	5	6	7	8	9
Very Hard		Somewhat Hard			Somewhat Easy		Very Easy	

Pilot 1: 5
Pilot 2: 7
Pilot 3: 9

Pilot 4: 1
Pilot 5: 4
Pilot 6: 5

χ = 5.16
σ = 2.71

NASA SVS HUD

3. Evaluate the ease of using the HUD photo-texture during the approach to rwy. 25

EASE OF USE OF HUD PHOTO TO RWY. 25								
1	2	3	4	5	6	7	8	9
Very Hard		Somewhat Hard			Somewhat Easy		Very Easy	

Pilot 1: 7
Pilot 2: 8
Pilot 3: 9

Pilot 4: 7
Pilot 5: 7
Pilot 6: 7

χ = 7.5
σ = 0.83

4. Evaluate the ease of using the HUD generic-texture during the approach to rwy. 25

EASE OF USE OF HUD GENERIC TO RWY. 25								
1	2	3	4	5	6	7	8	9
Very Hard		Somewhat Hard			Somewhat Easy		Very Easy	

Pilot 1: 5
Pilot 2: 8
Pilot 3: 9

Pilot 4: 7
Pilot 5: 7
Pilot 6: 4

χ = 6.66
σ = 1.86

5. Evaluate the ease of using the HUD photo-texture during the approach to rwy. 7

EASE OF USE OF HUD PHOTO TO RWY. 7								
1	2	3	4	5	6	7	8	9
Very Hard		Somewhat Hard			Somewhat Easy		Very Easy	

Pilot 1: 3
Pilot 2: 8
Pilot 3: 9

Pilot 4: 7
Pilot 5: 7
Pilot 6: 7

χ = 6.83
σ = 2.04

6. Evaluate the ease of using the HUD generic-texture during the approach to rwy. 7

EASE OF USE OF HUD GENERIC TO RWY. 7								
1	2	3	4	5	6	7	8	9
Very Hard		Somewhat Hard			Somewhat Easy		Very Easy	

Pilot 1: 6
Pilot 2: 8
Pilot 3: 9

Pilot 4: 7
Pilot 5: 7
Pilot 6: 4

χ = 6.83
σ = 1.72

7. Evaluate the ease of performing a missed approach to rwy. 25 using the HUD generic-texture display concept

EASE OF USE OF HUD GENERIC TO MISSED APPROACH RWY. 25								
3	4	5	6					
Very Hard		Somewhat Hard			Somewhat Easy		Very Easy	

Pilot 1: 5
Pilot 2: 7
Pilot 3: 9

Pilot 4: 7
Pilot 5: 7
Pilot 6: 4

χ = 6.5
σ = 1.76

You responded that the ease of using the HUD generic-texture during the approach to rwy 7 was _________ during your first day of flight evaluation. Please comment on the perceived differences (in rating if there is one) between using the generic-texture HUD to rwy. 7 and rwy. 25.

Pilot 1: No differences
Pilot 2: No differences
Pilot 3: No differences
Pilot 4: No differences
Pilot 5: No differences
Pilot 6: Generic harder

8. Please rate the workload associated between the two different approaches. We can define workload as: "the degree of cognitive processing capacity required to perform the flight task approach adequately". Please rate the workload in using the HUD generic-texture during the approach to rwy. 7

WORKLOAD TO RWY. 7 USING HUDGENERIC								
1	2	3	4	5	6	7	8	9
Very High		Somewhat High			Somewhat Low			Very Low

Pilot 1: 5
Pilot 2: 7
Pilot 3: 6
Pilot 4: 8
Pilot 5: 6
Pilot 6: 6

$\chi = 6.33$
$\sigma = 1.03$

9. Please rate the workload in using the HUD generic-texture during the approach to rwy. 25

WORKLOAD TO RWY. 25 USING HUD GENERIC								
1	2	3	4	5	6	7	8	9
Very High		Somewhat High			Somewhat Low			Very Low

Pilot 1: 5
Pilot 2: 7
Pilot 3: 6
Pilot 4: 7
Pilot 5: 5
Pilot 6: 6

$\chi = 6.0$
$\sigma = 0.89$

10. Please rate the missed approach, rwy. 7 or rwy. 25, which was lower in workload with using the HUD generic-texture. _____________ rwy. 7 ___________ rwy. 25

Pilot 1: Equal
Pilot 2: Equal
Pilot 3: Equal
Pilot 4: Equal
Pilot 5: Equal
Pilot 6: Equal

11. Please evaluate your situation awareness during the two different approaches to rwy. 25 using the NASA SV HUD generic-texture display concept. We 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."

SA TO RWY. 25 USING HUD GENERIC								
1	2	3	4	5	6	7	8	9
Very Low		Somewhat Low			Somewhat High			Very High

Pilot 1: 5
Pilot 2: 8
Pilot 3: 8
Pilot 4: 8
Pilot 5: 6
Pilot 6: 4

χ = 6.5
σ = 1.74

12. Please evaluate your situation awareness during the two different approaches to rwy. 7 using the NASA SV HUD generic-texture display concept. We 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."

SA TO RWY. 7 USING HUD GENERIC								
1	2	3	4	5	6	7	8	9
Very Low		Somewhat Low			Somewhat High			Very High

Pilot 1: 5
Pilot 2: 8
Pilot 3: 8
Pilot 4: 8
Pilot 5: 5
Pilot 6: 4

χ = 6.33
σ = 1.86

13. Please evaluate your situation awareness during the approach to rwy. 25 using the NASA SV HUD photo-texture display concept. We 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."

SA TO RWY. 25 USING HUD PHOTO								
1	2	3	4	5	6	7	8	9
Very Low		Somewhat Low			Somewhat High			Very High

Pilot 1: 6
Pilot 2: 8
Pilot 3: 8
Pilot 4: 8
Pilot 5: 5
Pilot 6: 6

χ = 6.83
σ = 1.33

14. Please evaluate your situation awareness during the approach to rwy. 7 using the NASA SV HUD photo-texture display concept. We 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."

SA TO RWY. 7 USING HUD PHOTO								
1	2	3	4	5	6	7	8	9
Very Low		Somewhat Low			Somewhat High			Very High

Pilot 1: 6
Pilot 2: 8
Pilot 3: 8

Pilot 4: 8
Pilot 5: 5
Pilot 6: 5

χ = 6.66
σ = 1.50

15. Did the use of the NASA HUD significantly improve your situation awareness beyond the use of the EADI w/ flight director for approach to rwy. 25? Please rate how much more your level of situation awareness was enhanced.

SA IMPROVEMENT USING HUD OVER EADI Rwy. 25								
1	2	3	4	5	6	7	8	9
None		A Little			Somewhat			Significantly

Pilot 1: 6
Pilot 2: 7
Pilot 3: 9

Pilot 4: 9
Pilot 5: 7
Pilot 6: 9

χ = 7.83
σ = 1.33

16. Did the use of the NASA HUD significantly improve your situation awareness beyond the use of the EADI w/ flight director for approach to rwy. 7? Please rate how much more your level of situation awareness was enhanced.

SA IMPROVEMENT USING HUD OVER EADI Rwy. 7								
1	2	3	4	5	6	7	8	9
None		A Little			Somewhat			Significantly

Pilot 1: 5
Pilot 2: 8
Pilot 3: 9

Pilot 4: 9
Pilot 5: 7
Pilot 6: 9

χ = 7.83
σ = 1.60

17. Evaluate the ease of using the HUD generic-texture during the missed approach to rwy. 7

EASE OF USE OF HUD GENERIC TO MISSED APPROACH RWY. 7								
1	2	3	4	5	6	7	8	9
Very Hard		Somewhat Hard			Somewhat Easy			Very Easy

Pilot 1: 5
Pilot 2: 7
Pilot 3: 9
Pilot 4: 7
Pilot 5: 7
Pilot 6: 4

$\chi = 6.5$
$\sigma = 1.76$

18. Evaluate the ease of performing a missed approach to rwy. 7 using the HUD photo-texture display concept

EASE OF USE OF HUD PHOTO TO MISSED APPROACH RWY. 7								
1	2	3	4	5	6	7	8	9
Very Hard		Somewhat Hard			Somewhat Easy			Very Easy

Pilot 1: 5
Pilot 2: 7
Pilot 3: 9
Pilot 4: 7
Pilot 5: 7
Pilot 6: 4

$\chi = 6.5$
$\sigma = 1.76$

19. Please rate which NASA HUD display concept (e.g., generic) provided the best level of situation awareness in performing the missed approach to rwy. 7 (situation awareness defined 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.").

Pilot 1: Neither
Pilot 2: Photo
Pilot 3: Photo
Pilot 4: Photo
Pilot 5: Photo
Pilot 6: Photo

<u>NASA HUD Symbology</u>

20. Evaluate the ease of predicting flight path using the "follow-me aircraft":

EASE OF PREDICTING FLIGHT PATH								
1	2	3	4	5	6	7	8	9
Very Hard		Somewhat Hard			Somewhat Easy			Very Easy

Pilot 1: 7
Pilot 2: 7
Pilot 3: 6
Pilot 4: 8
Pilot 5: 8
Pilot 6: 7

$\chi = 7.16$
$\sigma = 0.75$

21. Evaluate the ease of using the tunnel for vertical flight path guidance

EASE OF TUNNEL FOR VERTICAL FLIGHT PATH GUIDANCE								
1	2	3	4	5	6	7	8	9
Very Hard		Somewhat Hard			Somewhat Easy			Very Easy

Pilot 1: 7
Pilot 2: 7
Pilot 3: 9

Pilot 4: 7
Pilot 5: 8
Pilot 6: 5

$\chi = 7.16$
$\sigma = 1.33$

22. Evaluate the ease of using the tunnel for lateral flight path guidance

EASE OF TUNNEL FOR LATERAL FLIGHT PATH GUIDANCE								
1	2	3	4	5	6	7	8	9
Very Hard		Somewhat Hard			Somewhat Easy			Very Easy

Pilot 1: 7
Pilot 2: 7
Pilot 3: 9

Pilot 4: 7
Pilot 5: 7
Pilot 6: 5

$\chi = 7.0$
$\sigma = 1.26$

<u>Size A Evaluation</u>

23. Evaluate the ease of interpreting airspeed information for Size A photo:

EASE OF INTERPRETING AIRSPEED INFORMATION SIZE A PHOTO								
1	2	3	4	5	6	7	8	9
Very Hard		Somewhat Hard			Somewhat Easy			Very Easy

Pilot 1: 8
Pilot 2: 9
Pilot 3: 6

Pilot 4: 8
Pilot 5: 9
Pilot 6: 6

$\chi = 7.66$
$\sigma = 1.36$

24. Evaluate the ease of interpreting airspeed information for Size A generic:

EASE OF INTERPRETING AIRSPEED INFORMATION SIZE A GENERIC								
1	2	3	4	5	6	7	8	9
Very Hard		Somewhat Hard			Somewhat Easy			Very Easy

Pilot 1: 8
Pilot 2: 9
Pilot 3: 8

Pilot 4: 8
Pilot 5: 9
Pilot 6: 6

$\chi = 8.0$
$\sigma = 1.09$

25. Evaluate the ease of interpreting flight path vectors for Size A photo:

EASE OF INTERPRETING FLIGHT PATH VECTORS SIZE A PHOTO								
1	2	3	4	5	6	7	8	9
Very Hard		Somewhat Hard			Somewhat Easy			Very Easy

Pilot 1: 8
Pilot 2: 8
Pilot 3: 8

Pilot 4: 9
Pilot 5: 8
Pilot 6: 8

χ = 8.16
σ = 0.41

26. Evaluate the ease of interpreting flight path vectors for Size A generic:

EASE OF INTERPRETING FLIGHT PATH VECTORS SIZE A GENERIC								
1	2	3	4	5	6	7	8	9
Very Hard		Somewhat Hard			Somewhat Easy			Very Easy

Pilot 1: 8
Pilot 2: 8
Pilot 3: 8

Pilot 4: 9
Pilot 5: 8
Pilot 6: 5

χ = 7.67
σ = 1.36

27. Evaluate the ease of interpreting altitude information for Size A photo:

EASE OF INTERPRETING ALTITUDE INFORMATION SIZE A PHOTO								
1	2	3	4	5	6	7	8	9
Very Hard		Somewhat Hard			Somewhat Easy			Very Easy

Pilot 1: 8
Pilot 2: 9
Pilot 3: 6

Pilot 4: 8
Pilot 5: 8
Pilot 6: 5

χ = 7.33
σ = 1.51

28. Evaluate the ease of interpreting altitude information for Size A generic:

EASE OF INTERPRETING ALTITUDE INFORMATION SIZE A GENERIC								
1	2	3	4	5	6	7	8	9
Very Hard		Somewhat Hard			Somewhat Easy			Very Easy

Pilot 1: 8
Pilot 2: 9
Pilot 3: 6

Pilot 4: 8
Pilot 5: 8
Pilot 6: 5

χ = 7.33
σ = 1.51

29. Evaluate the ease of interpreting vertical speed information for Size A photo:

EASE OF INTERPRETING VERTICAL SPEED INFORMATION SIZE A PHOTO								
1	2	3	4	5	6	7	8	9
Very Hard		Somewhat Hard			Somewhat Easy			Very Easy

Pilot 1: 8
Pilot 2: 8
Pilot 3: 6

Pilot 4: 8
Pilot 5: 7
Pilot 6: 5

$\chi = 7.0$
$\sigma = 1.26$

30. Evaluate the ease of interpreting vertical speed information for Size A generic:

EASE OF INTERPRETING VERTICAL SPEED INFORMATION SIZE A GENERIC								
1	2	3	4	5	6	7	8	9
Very Hard		Somewhat Hard			Somewhat Easy			Very Easy

Pilot 1: 8
Pilot 2: 8
Pilot 3: 6

Pilot 4: 8
Pilot 5: 7
Pilot 6: 5

$\chi = 7.0$
$\sigma = 1.26$

31. Evaluate the ease of interpreting the ILS/Precision approach deviation indicators for Size A photo

EASE OF INTERPRETING ILS/PRECISION APPROACH INDICATORS SIZE A PHOTO								
1	2	3	4	5	6	7	8	9
Very Hard		Somewhat Hard			Somewhat Easy			Very Easy

Pilot 1: 8
Pilot 2: 8
Pilot 3: 9

Pilot 4: 7
Pilot 5: 8
Pilot 6: 7

$\chi = 7.83$
$\sigma = 0.75$

32. Evaluate the ease of interpreting the ILS/Precision approach deviation indicators Size A generic

EASE OF INTERPRETING ILS/PRECISION APPROACH INDICATORS SIZE A GENERIC								
1	2	3	4	5	6	7	8	9
Very Hard		Somewhat Hard			Somewhat Easy			Very Easy

Pilot 1: 8
Pilot 2: 8
Pilot 3: 9

Pilot 4: 7
Pilot 5: 8
Pilot 6: 7

$\chi = 7.83$
$\sigma = 0.75$

33. Evaluate the ease of predicting flight path using the "follow-me aircraft" for Size A photo:

EASE OF PREDICTING FLIGHT PATH INFORMATION SIZE A PHOTO								
1	2	3	4	5	6	7	8	9
Very Hard		Somewhat Hard			Somewhat Easy			Very Easy

Pilot 1: 6
Pilot 2: 7
Pilot 3: 9

Pilot 4: 8
Pilot 5: 7
Pilot 6: 7

$\chi = 7.33$
$\sigma = 1.03$

34. Evaluate the ease of predicting flight path using the "follow-me aircraft" for Size A generic:

EASE OF PREDICTING FLIGHT PATH INFORMATION SIZE A GENERIC								
1	2	3	4	5	6	7	8	9
Very Hard		Somewhat Hard			Somewhat Easy			Very Easy

Pilot 1: 6
Pilot 2: 7
Pilot 3: 9

Pilot 4: 8
Pilot 5: 7
Pilot 6: 7

$\chi = 7.33$
$\sigma = 1.03$

35. Evaluate the ease of using the tunnel for vertical flight path guidance for Size A photo:

EASE OF USING TUNNEL FOR VERTICAL PATH GUIDANCE SIZE A PHOTO								
1	2	3	4	5	6	7	8	9
Very Hard		Somewhat Hard			Somewhat Easy			Very Easy

Pilot 1: 5
Pilot 2: 7
Pilot 3: 4

Pilot 4: 7
Pilot 5: 8
Pilot 6: 6

$\chi = 6.16$
$\sigma = 1.47$

36. Evaluate the ease of using the tunnel for vertical flight path guidance for Size A generic:

EASE OF USING TUNNEL FOR VERTICAL PATH GUIDANCE SIZE A GENERIC								
1	2	3	4	5	6	7	8	9
Very Hard		Somewhat Hard			Somewhat Easy			Very Easy

Pilot 1: 5
Pilot 2: 7
Pilot 3: 5

Pilot 4: 6
Pilot 5: 8
Pilot 6: 7

$\chi = 6.33$
$\sigma = 1.21$

37. Evaluate the ease of using the tunnel for lateral flight path guidance for Size A photo:

EASE OF USING TUNNEL FOR LATERAL PATH GUIDANCE SIZE A PHOTO								
1	2	3	4	5	6	7	8	9
Very Hard		Somewhat Hard			Somewhat Easy		Very Easy	

Pilot 1: 5
Pilot 2: 7
Pilot 3: 4

Pilot 4: 7
Pilot 5: 7
Pilot 6: 6

$\chi = 6.0$
$\sigma = 1.26$

38. Evaluate the ease of using the tunnel for lateral flight path guidance for Size A generic:

EASE OF USING TUNNEL FOR LATERAL PATH GUIDANCE SIZE A GENERIC								
1	2	3	4	5	6	7	8	9
Very Hard		Somewhat Hard			Somewhat Easy		Very Easy	

Pilot 1: 5
Pilot 2: 7
Pilot 3: 5

Pilot 4: 7
Pilot 5: 7
Pilot 6: 6

$\chi = 6.16$
$\sigma = 0.98$

39. Please rate the workload associated between the two different missed approaches using the NASA Size A **photo-texture** display concept. We can define workload as: “the degree of cognitive processing capacity required to perform the flight task approach adequately”. Runway 25:

WORKLOAD TO RWY. 25 SIZE A PHOTO								
1	2	3	4	5	6	7	8	9
Very High		Somewhat High			Somewhat Low		Very Low	

Pilot 1: 5
Pilot 2: 3
Pilot 3: 5

Pilot 4: 8
Pilot 5: 9
Pilot 6: 7

$\boldsymbol{\chi = 6.16}$
$\boldsymbol{\sigma = 2.22}$

40. Please rate the workload associated between the two different missed approaches using the NASA Size A **photo-texture** display concept. We can define workload as: “the degree of cognitive processing capacity required to perform the flight task approach adequately”. Runway 7:

WORKLOAD TO RWY. 7 SIZE A PHOTO								
1	2	3	4	5	6	7	8	9
Very High		Somewhat High			Somewhat Low		Very Low	

Pilot 1: 5
Pilot 2: 3
Pilot 3: 7

Pilot 4: 6
Pilot 5: 9
Pilot 6: 6

$\boldsymbol{\chi = 6.0}$
$\boldsymbol{\sigma = 2.0}$

41.Please rate the workload associated between the two different missed approaches using the NASA Size A **generic-texture** display concept. Runway 25:

WORKLOAD TO RWY. 25 SIZE A GENERIC								
1	2	3	4	5	6	7	8	9
Very High		Somewhat High			Somewhat Low			Very Low

Pilot 1: 5
Pilot 2: 3
Pilot 3: 7

Pilot 4: 8
Pilot 5: 8
Pilot 6: 5

χ = 6.0
σ = 2.0

42. Please rate the workload associated between the two different missed approaches using the NASA Size A **generic-texture** display concept. Runway 7:

WORKLOAD TO RWY. 7 SIZE A GENERIC								
1	2	3	4	5	6	7	8	9
Very High		Somewhat High			Somewhat Low			Very Low

Pilot 1: 5
Pilot 2: 3
Pilot 3: 7

Pilot 4: 6
Pilot 5: 8
Pilot 6: 5

χ = 5.67
σ = 1.75

43. Please evaluate the level of situation awareness experienced during the missed approach to rwy. 25 for Size A **photo**. We 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."

SA TO RWY 25 SIZE A PHOTO								
1	2	3	4	5	6	7	8	9
Very Low		Somewhat Low			Somewhat High			Very High

Pilot 1: 7
Pilot 2: 8
Pilot 3: 7

Pilot 4: 9
Pilot 5: 9
Pilot 6: 7

χ = 7.83
σ = 0.98

44. Please evaluate the level of situation awareness experienced during the missed approach to rwy. 25 for Size A **generic**. We 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."

SA TO RWY. 25 SIZE A GENERIC								
1	2	3	4	5	6	7	8	9
Very Low		Somewhat Low			Somewhat High			Very High

Pilot 1: 5
Pilot 2: 8
Pilot 3: 7
Pilot 4: 8
Pilot 5: 6
Pilot 6: 7

χ = 6.83
σ = 1.16

45. Please evaluate the level of situation awareness experienced during the missed approach to rwy. 7 for Size A **photo**. We 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."

SA TO RWY 7 SIZE A PHOTO								
1	2	3	4	5	6	7	8	9
Very Low		Somewhat Low			Somewhat High			Very High

Pilot 1: 7
Pilot 2: 8
Pilot 3: 7
Pilot 4: 9
Pilot 5: 9
Pilot 6: 7

χ = 7.83
σ = 0.98

46. Please evaluate the level of situation awareness experienced during the missed approach to rwy. 7 for Size A **generic**. We 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."

SA TO RWY. 7 SIZE A GENERIC								
1	2	3	4	5	6	7	8	9
Very Low		Somewhat Low			Somewhat High			Very High

Pilot 1: 6
Pilot 2: 8
Pilot 3: 7
Pilot 4: 8
Pilot 5: 6
Pilot 6: 7

χ = 7.0
σ = 0.89

Size X Display Concept Evaluation

47. Evaluate the ease of interpreting airspeed information for Size X photo:

EASE OF INTERPRETING AIRSPEED INFORMATION SIZE X PHOTO								
1	2	3	4	5	6	7	8	9
Very Hard		Somewhat Hard			Somewhat Easy			Very Easy

Pilot 1: 6
Pilot 2: 8
Pilot 3: 9
Pilot 4: 9
Pilot 5: 9
Pilot 6: 7

$\chi = 8.0$
$\sigma = 1.26$

48. Evaluate the ease of interpreting airspeed information for Size X generic:

EASE OF INTERPRETING AIRSPEED INFORMATION SIZE X GENERIC								
1	2	3	4	5	6	7	8	9
Very Hard		Somewhat Hard			Somewhat Easy			Very Easy

Pilot 1: 6
Pilot 2: 8
Pilot 3: 9
Pilot 4: 9
Pilot 5: 9
Pilot 6: 7

$\chi = 8.0$
$\sigma = 1.26$

49. Evaluate the ease of interpreting flight path vectors for Size X photo:

EASE OF INTERPRETING FLIGHT PATH VECTORS SIZE X PHOTO								
1	2	3	4	5	6	7	8	9
Very Hard		Somewhat Hard			Somewhat Easy			Very Easy

Pilot 1: 6
Pilot 2: 8
Pilot 3: 9
Pilot 4: 7
Pilot 5: 9
Pilot 6: 7

$\chi = 7.66$
$\sigma = 1.21$

50. Evaluate the ease of interpreting flight path vectors for Size X generic:

EASE OF INTERPRETING FLIGHT PATH VECTORS SIZE X GENERIC								
1	2	3	4	5	6	7	8	9
Very Hard		Somewhat Hard			Somewhat Easy			Very Easy

Pilot 1: 6
Pilot 2: 7
Pilot 3: 9
Pilot 4: 7
Pilot 5: 9
Pilot 6: 7

$\chi = 7.5$
$\sigma = 1.22$

51. Evaluate the ease of interpreting altitude information for Size X photo:

EASE OF INTERPRETING ALTITUDE INFORMATION SIZE X PHOTO								
1	2	3	4	5	6	7	8	9
Very Hard		Somewhat Hard			Somewhat Easy		Very Easy	

Pilot 1: 6
Pilot 2: 7
Pilot 3: 9

Pilot 4: 8
Pilot 5: 9
Pilot 6: 8

$\chi = 7.83$
$\sigma = 1.17$

52. Evaluate the ease of interpreting altitude information for Size X generic:

EASE OF INTERPRETING ALTITUDE INFORMATION SIZE X GENERIC								
1	2	3	4	5	6	7	8	9
Very Hard		Somewhat Hard			Somewhat Easy		Very Easy	

Pilot 1: 6
Pilot 2: 8
Pilot 3: 9

Pilot 4: 8
Pilot 5: 9
Pilot 6: 8

$\chi = 8.0$
$\sigma = 1.09$

53. Evaluate the ease of interpreting vertical speed information for Size X photo:

EASE OF INTERPRETING VERTICAL SPEED INFORMATION SIZE X PHOTO								
1	2	3	4	5	6	7	8	9
Very Hard		Somewhat Hard			Somewhat Easy		Very Easy	

Pilot 1: 6
Pilot 2: 7
Pilot 3: 9

Pilot 4: 8
Pilot 5: 9
Pilot 6: 7

$\chi = 7.66$
$\sigma = 1.21$

54. Evaluate the ease of interpreting vertical speed information for Size X generic:

EASE OF INTERPRETING VERTICAL SPEED INFORMATION SIZE X GENERIC								
1	2	3	4	5	6	7	8	9
Very Hard		Somewhat Hard			Somewhat Easy		Very Easy	

Pilot 1: 6
Pilot 2: 8
Pilot 3: 9

Pilot 4: 8
Pilot 5: 9
Pilot 6: 7

$\chi = 7.83$
$\sigma = 1.17$

55. Evaluate the ease of interpreting the ILS/Precision approach deviation indicators for Size X photo

EASE OF INTERPRETING ILS/PRECISION APPROACH INDICATORS SIZE X PHOTO								
1	2	3	4	5	6	7	8	9
Very Hard		Somewhat Hard			Somewhat Easy			Very Easy

Pilot 1: 6	Pilot 4: 9	χ = 7.83
Pilot 2: 8	Pilot 5: 8	σ = 1.17
Pilot 3: 9	Pilot 6: 7	

56. Evaluate the ease of interpreting the ILS/Precision approach deviation indicators Size X generic

EASE OF INTERPRETING ILS/PRECISION APPROACH INDICATORS SIZE X GENERIC								
1	2	3	4	5	6	7	8	9
Very Hard		Somewhat Hard			Somewhat Easy			Very Easy

Pilot 1: 6	Pilot 4: 9	χ = 7.83
Pilot 2: 8	Pilot 5: 8	σ = 1.17
Pilot 3: 9	Pilot 6: 7	

57. Evaluate the ease of predicting flight path using the “follow-me aircraft” for Size X photo:

EASE OF PREDICTING FLIGHT PATH INFORMATION SIZE X PHOTO								
1	2	3	4	5	6	7	8	9
Very Hard		Somewhat Hard			Somewhat Easy			Very Easy

Pilot 1: 7	Pilot 4: 7	χ = 5.83
Pilot 2: 7	Pilot 5: 8	σ = 2.79
Pilot 3: 4	Pilot 6: 8	

58. Evaluate the ease of predicting flight path using the “follow-me aircraft” for Size X generic:

EASE OF PREDICTING FLIGHT PATH INFORMATION SIZE X GENERIC								
1	2	3	4	5	6	7	8	9
Very Hard		Somewhat Hard			Somewhat Easy			Very Easy

Pilot 1: 7	Pilot 4: 7	χ = 6.83
Pilot 2: 7	Pilot 5: 8	σ = 1.47
Pilot 3: 4	Pilot 6: 8	

59. Evaluate the ease of using the tunnel for vertical flight path guidance for Size X photo:

EASE OF USING TUNNEL FOR VERTICAL PATH GUIDANCE SIZE X PHOTO								
1	2	3	4	5	6	7	8	9
Very Hard		Somewhat Hard			Somewhat Easy		Very Easy	

Pilot 1: 6
Pilot 2: 7
Pilot 3: 7

Pilot 4: 9
Pilot 5: 8
Pilot 6: 8

$\chi = 6.67$
$\sigma = 2.50$

60. Evaluate the ease of using the tunnel for vertical flight path guidance for Size X generic:

EASE OF USING TUNNEL FOR VERTICAL PATH GUIDANCE SIZE X GENERIC								
1	2	3	4	5	6	7	8	9
Very Hard		Somewhat Hard			Somewhat Easy		Very Easy	

Pilot 1: 6
Pilot 2: 7
Pilot 3: 7

Pilot 4: 9
Pilot 5: 8
Pilot 6: 8

$\chi = 6.67$
$\sigma = 2.50$

61. Evaluate the ease of using the tunnel for lateral flight path guidance for Size X photo:

EASE OF USING TUNNEL FOR LATERAL PATH GUIDANCE SIZE X PHOTO								
1	2	3	4	5	6	7	8	9
Very Hard		Somewhat Hard			Somewhat Easy		Very Easy	

Pilot 1: 6
Pilot 2: 7
Pilot 3: 7

Pilot 4: 9
Pilot 5: 7
Pilot 6: 8

$\chi = 6.5$
$\sigma = 2.43$

62. Evaluate the ease of using the tunnel for lateral flight path guidance for Size X generic:

EASE OF USING TUNNEL FOR LATERAL PATH GUIDANCE SIZE X GENERIC								
1	2	3	4	5	6	7	8	9
Very Hard		Somewhat Hard			Somewhat Easy		Very Easy	

Pilot 1: 6
Pilot 2: 7
Pilot 3: 7

Pilot 4: 9
Pilot 5: 7
Pilot 6: 8

$\chi = 6.0$
$\sigma = 2.60$

63. Please rate the workload associated between the two different missed approaches using the NASA Size X **photo-texture** display concept. We can define workload as: "the degree of cognitive processing capacity required to perform the flight task approach adequately" Runway 25:

WORKLOAD TO RWY. 25 SIZE X PHOTO								
1	2	3	4	5	6	7	8	9
Very High		Somewhat High			Somewhat Low			Very Low

Pilot 1: 5
Pilot 2: 4
Pilot 3: 7

Pilot 4: 8
Pilot 5: 7
Pilot 6: 7

χ = 6.0
σ = 1.54

64. Please rate the workload associated between the two different missed approaches using the NASA Size X **photo-texture** display concept. We can define workload as: "the degree of cognitive processing capacity required to perform the flight task approach adequately" Runway 7:

WORKLOAD TO RWY. 7 SIZE X PHOTO								
1	2	3	4	5	6	7	8	9
Very High		Somewhat High			Somewhat Low			Very Low

Pilot 1: 5
Pilot 2: 4
Pilot 3: 7

Pilot 4: 7
Pilot 5: 7
Pilot 6: 7

χ = 6.16
σ = 1.33

65. Please rate the workload associated between the two different missed approaches using the NASA Size X **generic-texture** display concept. Runway 25:

WORKLOAD TO RWY. 25 SIZE X GENERIC								
1	2	3	4	5	6	7	8	9
Very High		Somewhat High			Somewhat Low			Very Low

Pilot 1: 5
Pilot 2: 5
Pilot 3: 7

Pilot 4: 8
Pilot 5: 6
Pilot 6: 7

χ = 6.33
σ = 1.21

66. Please rate the workload associated between the two different missed approaches using the NASA Size X **generic-texture** display concept. Runway 7:

WORKLOAD TO RWY. 7 SIZE X GENERIC								
1	2	3	4	5	6	7	8	9
Very High		Somewhat High			Somewhat Low		Very Low	

Pilot 1: 5
Pilot 2: 5
Pilot 3: 7

Pilot 4: 7
Pilot 5: 7
Pilot 6: 7

χ = 6.33
σ = 1.03

67. Please evaluate the level of situation awareness experienced during the missed approach to rwy. 25 for each display concept. We 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." Size X Photo-texture:

SA TO RWY 25 SIZE X PHOTO								
1	2	3	4	5	6	7	8	9
Very Low		Somewhat Low			Somewhat High		Very High	

Pilot 1: 3
Pilot 2: 8
Pilot 3: 9

Pilot 4: 9
Pilot 5: 9
Pilot 6: 7

χ = 7.5
σ = 2.34

68. Please evaluate the level of situation awareness experienced during the missed approach to rwy. 25 for each display concept. We 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." Size X Generic-texture:

SA TO RWY. 25 SIZE X GENERIC								
1	2	3	4	5	6	7	8	9
Very Low		Somewhat Low			Somewhat High		Very High	

Pilot 1: 4
Pilot 2: 8
Pilot 3: 9

Pilot 4: 8
Pilot 5: 9
Pilot 6: 6

χ = 7.33
σ = 1.97

69. Please evaluate the level of situation awareness experienced during the missed approach to rwy. 7 for each display concept. We 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." Size X Photo-texture:

SA TO RWY 7 SIZE X PHOTO								
1	2	3	4	5	6	7	8	9
Very Low		Somewhat Low			Somewhat High			Very High

Pilot 1: 3
Pilot 2: 7
Pilot 3: 9

Pilot 4: 9
Pilot 5: 9
Pilot 6: 7

χ = 7.33
σ = 2.33

70. Please evaluate the level of situation awareness experienced during the missed approach to rwy. 7 for each display concept. We 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." Size X Generic-texture:

SA TO RWY. 7 SIZE X GENERIC								
1	2	3	4	5	6	7	8	9
Very Low		Somewhat Low			Somewhat High			Very High

Pilot 1: 4
Pilot 2: 7
Pilot 3: 9

Pilot 4: 8
Pilot 5: 9
Pilot 6: 7

χ = 7.33
σ = 1.86

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14. ABSTRACT
NASA's Synthetic Vision Systems (SVS) Project is striving to eliminate poor visibility as a causal factor in aircraft accidents as well as enhance operational capabilities of all aircraft through the display of computer generated imagery derived from an onboard database of terrain, obstacle, and airport information. To achieve these objectives, NASA 757 flight test research was conducted at the Eagle-Vail, Colorado airport to evaluate three SVS display types (Head-up Display, Head-Down Size A, Head-Down Size X) and two terrain texture methods (photo-realistic, generic) in comparison to the simulated Baseline Boeing-757 Electronic Attitude Direction Indicator and Navigation / Terrain Awareness and Warning System displays. The results of the experiment showed significantly improved situation awareness, performance, and workload for SVS concepts compared to the Baseline displays and confirmed the retrofit capability of the Head-Up Display and Size A SVS concepts. The research also demonstrated that the tunnel guidance display concept used within the SVS concepts achieved required navigation performance (RNP) criteria.

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

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