TERRAIN PORTRAYAL FOR HEAD-DOWN DISPLAYS FLIGHT TEST

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Abstract

The Synthetic Vision Systems General Aviation (SVS-GA) element of NASA's Aviation Safety Program is developing technology to eliminate low visibility induced General Aviation (GA) accidents through the application of synthetic vision techniques. SVS displays present computer generated 3-dimensional imagery of the surrounding terrain to greatly enhance pilot's situation awareness (SA), reducing or eliminating Controlled Flight into Terrain (CFIT), as well as Low-Visibility Loss of Control (LVLOC) accidents. In addition to substantial safety benefits, SVS displays have many potential operational benefits that can lead to flight in instrument meteorological conditions (IMC) resembling those conducted in visual meteorological conditions (VMC). Potential benefits could include lower landing minimums, more approach options, reduced training time, etc. SVS conducted research will develop display concepts providing the pilot with an unobstructed view of the outside terrain, regardless of weather conditions and time of day.

A critical component of SVS displays is the appropriate presentation of terrain to the pilot. The relationship between the realism of the terrain presentation and resulting enhancements of pilot SA and pilot performance has been largely undefined. Comprised of coordinated simulation and flight test efforts, the terrain portrayal for head-down displays (TP-HDD) test series examined the effects of two primary elements of terrain portrayal: variations of digital elevation model (DEM) resolution and terrain texturing. Variations in DEM resolution ranged from sparsely spaced (30 arc-sec/2,953ft) to very closely spaced data (1 arc-sec/98 ft). Variations in texture involved three primary methods: constant color, elevation-based generic, and photo-realistic, along with a secondary depth cue enhancer in the form of a fishnet grid overlay. The TP-HDD test series was designed to provide comprehensive data to enable design trades to optimize all SVS applications, as well as develop requirements and recommendations to facilitate the implementation and certification of SVS displays.

The TP-HDD flight experiment utilized the NASA LaRC Cessna 206 Stationaire and evaluated eight terrain portrayal concepts in an effort to confirm and extend results from the previously conducted TP-HDD simulation experiment. A total of 15 evaluation pilots, of various qualifications, accumulated over 75 hours of dedicated research flight time at Newport News (PHF) and Roanoke (ROA), VA, airports from August through October, 2002. This report will present results from the portion of testing conducted at Roanoke, VA.

Introduction

GA aircraft comprise 85 percent of the total number of civil aircraft in the United States of America (USA). In a report of the National Transportation Safety Board (NTSB) accident database [1], GA accounted for 85 percent of all accidents and 65 percent of all fatalities. The combination of night and IMC increased the proportion of fatal to total accidents to 64.3 percent, making it the most deadly general aviation flight environment.

The ability of a pilot to ascertain critical information through visual perception can be limited by various weather phenomena, such as rain, fog, and snow. Since the beginning of flight, the aviation industry has continuously developed a variety of devices, such as attitude indicators, radio navigation, and instrument landing systems to overcome these issues. Recent advances include moving map displays, incorporating advances in navigational accuracies from the Global Positioning System, and enhanced ground proximity warning systems. However, all of the aircraft information display concepts developed to date require the pilot to perform various additional levels of mental model development and maintenance and information decoding in a real-time environment when outside visibility is restricted [2].

SVS technology will allow this *visibility* problem to be solved with a *visibility* solution. By providing the pilot with a synthetic vision display his SA can be dramatically increased during low visibility conditions. These displays employ computer-generated terrain imagery to present three dimensional, perspective, out the window scenes with sufficient information and realism to enable operations equivalent to those of a bright, clear day, regardless of the outside weather conditions [2, through 13].

An essential component of all SVS displays is the synthetic terrain. SVS terrain provides information to the pilot regarding the outside world and also serves as the backdrop for integration of the other elements of the display (such as flight data information, guidance symbology, etc.). Effective terrain presentation, that conveys the optimum information to the pilot with the lowest mental workload, is paramount to successful SVS development and implementation.

Numerous publications [2 through 13] are available describing various terrain depiction techniques for tactical primary flight displays (PFDs) and heads-up-displays (HUDs) and strategic navigation display (ND) elements of Multi-Function Displays (MFDs). These techniques include, but are not limited to, ridge lines, grid patterns (equal and non-equal spacing), color-coded contour lines, varying color textures based on elevation, photorealistic textures, and textures with an embedded grid pattern. Textures increase terrain realism by increasing the level of detail per polygon, thus providing additional cues for position and closure rate (height and range) estimates. Flight tests have demonstrated that adding a textured terrain skin to the EADIs and PFDs gave pilots a better awareness of their height above the ground. However, references 2 through 13 did not comprehensively investigate terrain portrayal techniques as applied to SVS displays, providing only information for certain specific cases with limited comparisons.

Recently conducted work at the University of Iowa [11] provides detailed information regarding SVS terrain portrayal. In this study, a broad spectrum of terrain portrayal techniques were examined using several types of experimentation methods. These included static and dynamic display evaluations combined with piloted simulations of a perspective terrain display located next to an EADI. The objective of reference 11 was to establish the minimum effective terrain portrayal technique to enable the use of currently certified computer platforms with limited capabilities. Reference 11 provides a wealth of data regarding human perception of SVS terrain portrayal techniques and shows that terrain resolution and texturing significantly affect human subjects' ability to maintain SA.

The TP-HDD test series extends previous research on the effects of DEM resolution and texturing and includes real-time piloted simulation and flight test evaluations, with integrated terrain and symbology, on SVS displays.

Objectives of Flight Test

The TP-HDD test series was conducted to address several critical aspects of SVS displays, which concentrated on core technology issues while identifying and addressing key certification issues. The objectives of the TP-HDD test series were to: 1) determine the effect of terrain texturing on situation awareness (SA) and pilot performance for SVS PFDs; 2) determine the effect of DEM resolution on SA and pilot performance for SVS PFDs; 3) establish field of view (FOV) recommendations for SVS PFDs; 4) demonstrate the efficacy of SVS displays for a comprehensive spectrum of pilots in both mountainous and flat-maritime environments; 5) demonstrate that non-instrument rated pilots are able to fly to an acceptable level of precision, with minimal training; using SVS PFDs with tunnel guidance symbology; 6) confirm and extend previously-conducted simulation results. This paper will partially address these objectives. Subsequent publications (NASA TPs) will present more complete treatments.

Method

To partially address these multiple objectives, the flight test involved eight display concepts (one without terrain and seven SVS variations), two evaluation maneuvers (an en route and a approach maneuver), and two pilot group classifications.

Participants

A total of 15 evaluation pilots (EPs) participated in this flight test effort. Seven EPs participated in the first part of the flight test (at Roanoke, VA.). Eight EPs participated in the second part of the flight test (at Newport News, VA.).

For the ROA portion of testing, which is the focus of this report, EPs were arranged into two groups. Private pilots with less then 400 total hours comprised the first group. The second group consisted of professional test pilots from NASA and Boeing, each having much greater then 1,000 flight-hours. All EPs participated in the preceding TP-HDD simulation study [12, 13].

Terrain Databases

Digital Elevation Models

DEM resolution defines the distance between elevation data points (post-spacing) for a given a given database. Three specific DEM resolutions were investigated during the TP-HDD experiment with the intent to cover a broad range of viable DEM options. The low resolution, 30 arc-sec (900m/2953ft post-spacing) DEM was selected because it is freely available and currently used in some industry SVS applications due to the low amount of computational power required for rendering. The medium resolution, 3 arc-second (90m/295ft post-spacing) DEM was selected since it is also relatively available, and should be easily available in the near future. The highest resolution, 1 arc-sec (30m/98ft post-spacing) DEM option was investigated in this experiment to form an upper bound for current consideration.

It should be noted that higher resolution databases are much larger in terms of the overall number of data points for a given area of coverage with higher computational expenses associated with manipulating and rendering this data. It also should be noted that the smallest polygon that can be created with a given DEM has sides equal to the distance between data points. For example, the smallest possible polygon employed with the 30 arc-sec DEM would have sides 2,953 feet long. Since the lower resolution DEMs are less populated, substantial terrain features might be excluded. The possibility of losing entire peaks as well as detailed terrain relief in the lower resolution databases exists.

Terrain-Texturing Concepts

Terrain-texturing refers to the method used to color the polygons that comprise the terrain database. The three primary texturing concepts tested were constant-color (CC), elevation-based generic (EBG), and photo-realistic (PR). The constant-color texturing concept was developed to represent a current industry concept that has completed the process of Federal Aviation Administration (FAA) certification in the Capstone-2 program. This texturing concept requires the minimal amount of computational resources for rendering. This computational reduction enhances the potential use of currently certified avionics platforms for SVS applications.

The elevation-based texturing concept consists of twelve equal-height coloring bands. These bands correspond to different absolute terrain elevation levels, similar to the colors employed for Visual Flight Rules (VFR) sectional charts. Lower terrain levels are colored with darker colors, higher terrain levels are assigned lighter colors. A certain shade of green was set to the field elevation. The lightest color was set to the highest terrain within 50 nm of ROA, approximately 4,000 ft MSL.

The photo-realistic texturing was derived from full color ortho-rectified 4 m satellite imagery data. The resulting scene was a highly realistic view due to the photographic imagery employed. PR texturing requires specialized computer-graphics resources that exceed current certified flight computer platforms primarily due to the large amount of texture memory required to create the realistic scene.

Cultural Feature Data

For the CC and EBG terrain textured display concepts, cultural features, such as roads and rivers, were included as objects in the terrain database. These objects were unnecessary for the PR terrain textured concepts since those features were supplied directly through the photo-texture images.

Fish Net Overlay Concept

In addition to the primary terrain texturing concepts, a fishnet (FN) grid overlay was employed for several display concepts. The theory of the FN grid involves placing grids of known size within the synthetic scene to facilitate pilots' depth perception. The potential benefits of the FN grid used in this study are cues for depth perception, distance, angular orientation and angular rates. The spacing of the FN overlay was 500 ft by 500 ft, regardless of the DEM resolution. The FN grid was dual-color (gray/white), to compensate for different coloring of features within the terrain databases (e.g., lighter colors of populated areas for the PR texture).

Airport Models and Objects

The ROA airport model included runways with all runway markings along with most significant airport buildings. Airport buildings were developed to appear like the actual buildings they represented if viewed from approximately 3 miles. All models were placed on top of the underlying terrain database. Objects greater then 200 ft high within 20 nm of ROA were represented by narrow rectangular barber-striped pole objects representing their actual height and location.

Generation of Terrain Databases

Research terrain databases were built and rendered using commercial off-the-shelf (COTS) tools. Terrain Experts' TerraVista was used to construct the database from digital elevation points and add one or more textures. MultiGen-Paradigm's Creator was used to create the three dimension (3D) models of airports, buildings, obstructions and other man made structures. Objects were created in OpenFlight format. The finished research terrain databases were rendered with Quantum3D/CG2 VTree. A variety of other COTS tools were also used including Okino PolyTrans, and ERDAS Imagine.

Resulting Display Concepts

Eight PFD concepts were employed for this flight test effort. The first display concept (shown in figure 1) (DC 1) was referred to as the Blue-Sky/Brown Ground (BSBG) baseline that replicated a basic PFD with no SVS terrain. The remaining seven DCs were created through variations of DEM and texturing as defined in Table 1. Figure 2 shows the CC+FN texture with 30 arc-sec DEM that represents an industry application of SVS technology (DC 2). Figure 3 shows the EBG texture concept with 1 arc-sec DEM (DC 4). Figure 4 shows the PR texture concept with a 1 arc-sec DEM (DC 6). Figures 5 and 6 illustrate the FN secondary texture concept applied to the EBG and PR texturing methods with the 3 arc-sec DEM (DCs 7, 8), respectively. While the FN was designed to enhance the EBG and PR primary texturing concepts, it was required for CC texturing, as no terrain information is visible without it.

Visual inspection of the DCs provided in figures 1 through 6 reveals the vast differences existing between them. Comparing DC 1 to DC 2, the presence of location-specific terrain is evident, especially in the distance where terrain rises above ownship altitude. DC 2 was considered to be the minimal SVS terrain portrayal concept. Comparing DC 4 to DC 2, and also to DC 1, the enhanced amount of terrain information being provided through the application of terrain coloring is evident for the EBG texturing (ignoring for the moment the variations in DEM resolution). Valleys and hills are easily distinguishable with EBG texturing. Photo-realistic texturing, as illustrated by DC 6, shows the comparative increase in the amount of terrain detail.

The presence of the FN texturing and effect of DEM resolution is illustrated through comparisons of DC 4 with DC 7 and DC 6 with DC 8. Generally, increasing DEM resolution from 3 to 1 arc-sec provides some more noticeable detail for terrain within 1 to 3 nm of the aircraft. Note the more defined ridgeline in the lower left corner of the images for the 1 arc-sec DEM concepts (DC 4 and DC 6). Due to the small size of the figures presented herein, this observation is somewhat compromised.

Texture\DEM	30 arc-sec	3 arc-sec	1 arc-sec
CC+FN	DC 2		
EBG		DC 3	DC 4
PR		DC 5	DC 6
EBG+FN		DC 7	
PR+FN		DC 8	

Table 1. Listing of Display Concepts Tested.

Pilot Selectable FOV and minification factor

For this experiment, FOV refers to the horizontal field of view of the image presented on the PFD unless otherwise specified. Vertical FOV was adjusted based on horizontal FOV using the research PFD's 4:3 aspect ratio. Pilots could select one of four FOVs: 22.5, 30, 60, and 90 degrees. The minification factor (MF) is defined as the amount of angular compression created when non-conformal imagery is displayed and is calculated by dividing the FOV by the conformal FOV of the display device. For this experiment, MFs tested were: 2.0, 2.7, 5.5, and 8.2.

Symbology

Basic Symbology

Basic symbology included on the PFD for all DCs tested for both maneuvers included air-data, orientation, and guidance information. Air-data information was presented by integrated airspeed and altitude tapes. A vertical speed indicator was included in the integrated altitude tape. A roll pointer with magnetic heading digital read-out, and a pitch ladder provided heading and attitude orientation information. Additional symbology components were elements that characterized the velocity vector cluster. This cluster employed a non-quickened velocity vector that depicted current aircraft flight path and track angle with an acceleration-along-flight-path indicator (off the left finlet of the velocity vector marker).

Guidance Symbology

Guidance symbology (see figure 1) was presented in the form of course deviation indicators and the tunnel in the sky and was displayed to the pilots for the approach maneuvers only. Vertical and lateral dogbone-shaped path deviation indicators provided the pilot with information regarding proximity of the aircraft to the center of the tunnel. Diamond shaped course deviation indicators were provided to show localizer and glideslope error. Both the dogbone-shaped path deviation indicators and diamond-shaped localizer/glideslope error deviation indicators were co-located on the same scales. Localizer and glideslope error information were generated within the research software.

The tunnel in the sky concept featured 400 feet wide by 320 feet tall uniform green boxes depicting the desired flight path for the approach scenario, providing most of the lateral and vertical path guidance. Tunnel spacing was dependent on FOV. For the wider FOV's, the tunnel boxes were closer together; for the smaller FOV's, the tunnel boxes were spaced farther apart (i.e., FOV=90°, distance between boxes = 965 ft; FOV=30°, distance between boxes = 4,685 ft). During turns, if the flight path required bank angle was greater than 5°, the boxes were tilted 20° to cue the turn.

The pilot-selected FOV was displayed digitally to the pilot in the lower left corner of the display below the airspeed tape. The size of the digital FOV readout was enlarged when FOV was being adjusted. After three seconds, the digital FOV readout was returned to nominal size.

Strategic Display

Strategic terrain display concepts, such as the United Parcel Service Aviation Technology (UPSAT) MX-20 MFD, augment information provided to pilots by SVS perspective displays. The presence of the MX-20 in this experiment provided the capability to evaluate the integrated information supplied by both the PFD and the MFD, as well as estimate the relative value of each type of display. The MX-20 was used in the terrain awareness mode only, and was located in the radio stack. On the MX-20 MFD, terrain awareness, route information, waypoints, and towers were portrayed. All display concepts were evaluated in the presence of the MX-20 MFD. See figure 7 for a photograph of the MX-20 during approach to Roanoke, VA. Terrain more then 2,000 ft below the aircraft was black, terrain between 2,000 ft and 500 ft below was green, terrain between 500 ft below and ownship altitude was yellow, terrain at or above ownship altitude was red.

Flight Test Aircraft

The NASA LaRC Cessna-206 H Stationaire (C-206) aircraft was employed for this study (see figure 8). Nominally a 6 passenger aircraft, it was particularly well suited to support this research effort due to its substantial payload carrying characteristics combined with a high-capacity alternator.

To support this test, a research pallet was fabricated to contain the research computer, power inverter, audio-video recorders, and air-data and heading reference system (ADAHRS). The research pallet was located in place of the middle left seat. The research computer was located approximately where the rear seat would have been. The research pilot's station was the front right seat. See figure 9 for a photograph of the instrument panel showing the location of the research PFD and MX-20.

Flight Test Equipment

Various pieces of research hardware were installed in the aircraft to support this flight test.

The most significant elements are included in this report.

ADAHRS

A Seagull GIA-2000 ADAHRS was employed for this flight test to provide all position, orientation, and air data. The GIA-2000 was a prototype ADAHRS designed to address the need for low-cost equipment to enable SVS-GA applications. Utilizing it for this test provided data to confirm its efficacy as a low-cost ADAHRS suitable for SVS-GA applications.

The ADAHRS provided aircraft acceleration (linear and angular) at 50 Hz. This high-rate data was combined with low-rate GPS position (supplied at 1 Hz) and pressure-based altitude data through a complementary filter to generate high-rate position information for the SVS display system. All air-data was supplied at 5 Hz.

Research Computer

The research computer employed for this flight test was a rack-mounted SGI/Integraph Zx10 dual-processor graphics workstation PC. The Zx10 had dual 1-GHz processors, 2-GB of random access memory (RAM), 60 GB hard-drive, and a 3DLabs Wildcat 4210 graphics card. The resulting research computer provided the capability to evaluate advanced SVS terrain portrayal concepts while taking advantage of many COTS software products.

Research PFD

The research PFD, purchased from Computer Dynamics, was a COTS 6" high-bright 4:3 aspect ratio Liquid Crystal Display (LCD) operated in VGA mode (640x480). The display was repackaged for this study. Refer to figure 9 for a photograph showing the installation of the research PFD. Employing a 24.5" eye reference point created a unity horizontal FOV of this device of approximately 11 degrees. Under these conditions, the research PFD provided a resolution of approximately 57 pixels per degree. This level of resolution approached the level of human perception of 60 pixels per degree.

Flight Test Engineer's Display

To provide the ability to control test parameters and monitor pilot performance, a 15" flight test operator's display was installed on the back of the front-right seat. For this test, the video generated for the research PFD was routed through a video distribution amplifier and distributed to both the research PFD and flight test engineer's display.

Control Position Transducers

In order to quantify pilot control activity, control position transducers (CPTs) were installed on the pitch, roll, yaw, throttle, and pitch-trim controls. These transducers were routed to the research computer through an Analog to Digital (A to D) card and their values were recorded.

Field of View Control

Pilots were able to select from four FOVs through a rotary knob, located adjacent to the lower left corner of the research PFD, or a push-button switch, located on the yoke. Selectable FOV choices were: 22.5, 30, 60, and 90 degrees.

Evaluation Maneuvers

En Route Maneuver

The en route maneuver required the evaluation pilot to maintain assigned heading, airspeed, and altitude values at appropriate points. The en route maneuver began 19 nm southwest of ROA, with a heading of 140° and an indicated airspeed of 100 knots (KIAS). The en route maneuver was initiated at 6,500 ft MSL (approximately 4,000 ft AGL). Pilots were required to fly straight and level for approximately 2.5 minutes, maintaining heading, airspeed, and altitude. With the help of the strategic display to identify a fly-by waypoint, the EPs were asked to execute a left turn, using 20 degrees of bank, to a heading of 050°, while simultaneously descending 1,500 ft (over rising terrain). For this maneuver, part of the descent took place during the 90° turn; the rest of the descent was completed while maintaining the second target heading. The target level-off altitude was 5,000 ft MSL (approximately 1,000 ft AGL). Overall, the maneuver lasted approximately 5 minutes.

EPs were asked to vary FOV during the entire maneuver to any desired setting. At the end of the maneuver, the EPs were asked to cycle through FOVs, one more time, to support their evaluations.

Approach Maneuver

The approach maneuver employed a straight and level right-turn 30-degree localizer intercept course for the Instrument Landing System (ILS) 33 approach into ROA. The touchdown zone elevation for runway 33 was 1,179 MSL. The task started 12 nm south of ROA at 3,000 ft MSL. This initial altitude provided approximately 800 ft clearance over a ridgeline that was crossed on the initial segment to enhance pilot evaluations of SVS terrain. With flaps were set to 10 degrees, an indicated airspeed of 90 KIAS was to be maintained throughout the maneuver. The subject pilots were tasked to follow the tunnel guidance symbology, roughly following a heading of approximately 300°, and join the localizer (roughly 10 nm from the threshold) and maintain 3,000 ft MSL until intercepting the glide slope at approximately 4.5 nm, then continue flying the approach to 200 ft AGL. EPs were asked to vary FOV during the entire maneuver to any desired setting.

Flight Test Operations

All flight test research operations were conducted in Visual Meteorological Conditions (VMC) clear of clouds. The safety pilot (SP) occupied the front-left seat and flight test engineer occupied the mid-right seat.

Each EP participated in two consecutive research flights lasting approximately 2 hours each. The first research flight generated data for the en route maneuver block. After an approximately 30-minute break on the ground outside of the aircraft, the second flight generated data for the approach maneuver block. To facilitate flight operations, the en route data flights usually took off just after sunrise (about 6:30am). The approach data flights took off at approximately 9:30am and were concluded at approximately 12pm.

The EP was required to wear a baseball hat with the brim adjusted to preclude forward vision out the window. This also resulted in highly limited outside peripheral vision as well. A baseball hat was selected instead of a traditional IFR training hood due to the training hood's restrictive field of view requiring the EP to rotate his head to be able to scan the MX-20 and research PFDs.

Prior to each set of research data runs, EPs were required to perform at least one training run for the en route and approach maneuvers. EPs could have additional training runs if needed. Usually, only one training run was required. EPs were informed as to which DC they were evaluating prior to the start of the run.

During the en route maneuver setup, EPs were subjected to some mild spatial disorientation maneuvering, lasting approximately 1 minute, during which they were required to look at the floor. Then, the aircraft was quickly stabilized at the desired test condition (altitude, airspeed, and heading), EPs were instructed to then look at the research instruments (MX-20 and research PFD), and control was transferred to the EP. Control was transferred back to the SP at the end of the en route maneuver after the FOV cycling was complete.

For the approach maneuver, control was transferred to the EPs when guidance boxes (of the guidance tunnel) first became visible on the research PFD, approximately 1 nm from the start of the approach path. Control of the aircraft was transferred back to the SP at the end of the run (approximately 200 ft AGL).

EPs filled out run questionnaires between evaluation maneuvers. Typically, 5 minutes were required to reset for the next evaluation maneuver, providing adequate time to complete the questionnaires.

Test Matrix

Evaluation maneuvers were blocked (en route or approach) with DCs being randomized to counter learning and fatigue effects. The en route block was always conducted first. For this flight test, the test matrix included evaluations for statistical quantitative data of DCs 1 through 6 and either 7 or 8. DCs 7 and 8 were the EBGFN-3 and PRFN-3 concepts. For each EP, only one of those FN concepts were tested for statistical data in order to reduce the total number of data runs per block (en route and approach) to 7 to keep flight durations to 2 hours. EPs were trained using the DC that was not part of their statistical data evaluation set (DC 7 or 8) to enable qualitative data to be gathered. EPs who were trained with DC 7 for the en route maneuver, were also trained with DC 7 for the approach maneuver.

Data Analyses and Results

Due to the large amount of data recorded and analyzed in this experiment, it is not practical to report on all significant aspects of the flight test in this paper. This document focuses mostly on texturing effects, while providing more general results for all DCs tested.

Qualitative Data

Questionnaires were administered after each evaluation run and after each EP's flight pair. Run questionnaires included Task Load Index (TLX), Situation Awareness Rating Tool (SART), Terrain Awareness, Stress, and Cooper-Harper elements. Post-flight questionnaires included Situational Awareness and Subjective Workload and Relative Dominance (SASWORD) comparisons for en route and approach maneuvers as well as an overall preference. In addition, post-flight questions also dealt with preferred FOVs, terrain information as provided by the MX-20 and PFD, the value of the guidance tunnel (for approach), and other issues.

Only terrain awareness data are presented for this report. For the en route maneuver, pilots indicated that they were much more aware of terrain for most of the SVS concepts tested than for the BSBG DC 1 concept. Terrain awareness ratings for the en route maneuver are presented in figure 10. This figure illustrates the level of increased terrain awareness for all SVS DCs. A statistical analysis performed on this data indicates that the effect of DC was highly significant. Subsequent post-hoc analysis produced two distinct groups. The group with the lowest level of terrain awareness consisted of BSBG (location-specific terrain awareness provided by the MX-20) and CCFN-30. The other six DCs were included in the second group. From figure 10, it can be seen that the level of terrain awareness for the CCFN-30 was closer to the BSBG then to the other SVS concepts. This agrees strongly with other pilots' comments regarding the general relationship between the CCFN-30, BSBG, and the other SVS concepts during the relatively low-workload en route maneuver.

Terrain awareness ratings for the approach maneuver are presented in figure 11. As was the case for the en route data, the effect of DC on terrain awareness was highly significant. However, for the approach data, subsequent post-hoc analysis created three separate groups. The group with the lowest terrain awareness consisted again of the BSBG and CCFN-30. All the PR textured concepts (PR-3, PR-1, and PRFN-3) comprised the intermediate group. All of the EBG textured concepts (EBG-3, EBG-1, and EBGFN-3), and the PR textured concepts without FN (PR-3, PR-1), comprised the group with the highest level of terrain awareness. The post-hoc groupings related well to other pilot comments indicating that the EBG textured DCs provided terrain information that was easier to interpret, which agrees with information contained in reference [11]. Important terrain features, such as the location of valleys and mountains, may be more difficult for the pilot to discern due to the masking effect of trees and other elements included in the photo-realistic texturing. Specific pilot comments reflected a desire to know when they were approaching a ground-based hazard without a need to know whether it was rocks, dirt, or trees.

Quantitative Data

In order to effectively analyze pilot control performance, both evaluation maneuvers were separated into segments. The seven segments for the en route maneuver were: 1) straight and level flight, 2) descending turn entry, 3) descending turn, 4) descending turn exit, 5) constant heading descent, 6) transition to straight and level flight, and 7) straight and level flight. For the approach maneuver, the eight segments were: 1) Localizer intercept, 2) level turn entry, 3) level turn, 4) level turn exit, 5) level localizer tracking, 6) glideslope intercept, 7) localizer and glideslope tracking, and 8) localizer and glideslope tracking below 600 ft AGL.

Pilot performance metrics, that quantified safe and desirable levels of pilot control of the aircraft, as the percent of the time that the pilots maintained desired (Level 1), adequate (Level 2), and below adequate performance, were established and analyzed. Level 1 performance for the en route maneuver required the pilot to maintain airspeed within +/- 10 kts, altitude within +/-100 ft, and heading and bank angle within +/-10 degrees, when appropriate. For the initial portion of the approach maneuver, desired path performance was +/- 100 ft laterally and +/-80 ft vertically, with +/- 10 kts of airspeed error. When the localizer course was captured, desired lateral performance was changed to be +/- 1 dot of localizer error. When the glideslope was captured, the desired vertical performance was changed to +/- 1 dot of glideslope error. This was done to enable the application of more established range-varying performance data for analysis. Adequate performance (Level-2) was considered to be twice desired limits.

En Route

The percentage of time pilots were able to maintain Level-1 performance, for the entire relatively low-workload en route maneuver, is presented in figure 12 as a function of DC. The only information elements available to the pilot for task accomplishment consisted of airspeed, altitude and heading cues (no tunnel or other guidance cues). Comparison of the SVS DCs with the BSBG show that, in general, pilots were able to remain within Level-1 performance approximately 97% of the time with a standard deviation of 4.8%. All of the SVS concepts, except the PR1, produced pilot performance results equivalent to the BSBG baseline.

An analysis of variance (ANOVA) was conducted on percentage of time within Level-1 performance with DC and pilot type as independent variables. Neither DC nor pilot type significantly affected the percentage of time within Level-1. Although not statistically significant, the mean time within Level-1 for the PR1 DC dropped to approximately 92%. In addition, the standard deviation for the PR1 also increased, becoming almost twice the average for all DCs, with 3 of the 7 pilots achieving Level-1 performance less than 90% of the time. Of these 3 pilots, 2 were from the low-time VFR group and one was from the high-time group. This result could be indicative of the increased amount of terrain detail due to the photo-realistic texturing combined with the high-resolution DEM, slowing the pilot's scan of the control parameters (airspeed, altitude, heading) for the PR1 DC. This result agrees with results from reference [11].

Approach

For the higher-workload approach task, the percentage of time pilots were within Level-1 performance for segment 7 is presented in figure 13. The information elements available to the pilot for task accomplishment consisted of the tunnel, the course deviation indicators and airspeed cues. Pilots were able to maintain Level-1 performance an average of 85% of the time with a standard deviation of 13.34%. An ANOVA performed on performance data for the entire approach task with DC and pilot type as independent variables revealed that DC did not significantly affect time within Level-1 ($F(7,29)=0.542$, $\alpha=0.796$), but pilot type was highly significant ($F(1,29)=9.23$, $\alpha=0.005$). The effect of pilot type on pilot performance for the entire approach task (averaged over all DCs) is presented in figure 14, where it can be seen that the low-time VFR pilots achieved Level-1 performance 81% of the time, while the high-time pilots achieved Level-1 performance 95% of the time. Although the effect of tunnel guidance has been demonstrated to be highly effective towards improving low-time pilot performance [13], pilot skill and experience still are highly significant factors.

The FAA Instrument Rating Practical Test Standards (PTS) [14] metric employed for evaluating performance on the ILS final approach segment allows no more than three-quarter-scale deflection of either the localizer or glide slope indications, while maintaining the specified airspeed to within 10 knots. For this test, low-time VFR pilots were only able to keep maximum glideslope error (averaged over all DCs) to within 75% of maximum deflection for 50% of the approaches conducted as illustrated in figure 15. Maximum airspeed error (averaged over all DCs) exceeded +/-10 kts for 80% of the approaches conducted and exceeded +/-19 kts for 5% of the approaches conducted as illustrated in figure 16. All of the approaches conducted by low-time VFR pilots controlled maximum localizer deviation to within 30% of maximum deflection (not shown).

It should be noted that data analyzed herein were digital in nature. Short increases in airspeed, resulting from turbulence, could introduce effects that might not be observed through cross-cockpit viewing of a conventional round dial airspeed indicator by an FAA examiner. Still, vertical path error and speed management emerged as areas requiring improvement for low-time pilots to meet IFR practical test standards.

The result that DC did not significantly affect pilot's performance may be attributed to the higher-workload task. Pilot comments regarding the approach task indicated that they were focusing more on the guidance symbology and not on the background terrain, explaining the lack of significant effect of terrain on pilot's performance. This comment is interesting since EPs provided definite responses regarding terrain awareness.

During this flight test, some issues were encountered regarding the characteristics of some of the symbology elements. Recall that the motion of the velocity vector was dependent on blending low-rate position with high-rate acceleration data. While the behavior of the velocity vector was deemed acceptable for this study, several options such as low-pass filtering with pitch-rate quickening, are available to improve its characteristics. Additionally, EPs were instructed to rely only on the airspeed data and acceleration indicator arrow, and not the tachometer, to manage airspeed. While this strategy appeared acceptable during pre-testing, improvements in the acceleration arrow performance, the inclusion of the tachometer, or both, could have improved airspeed control.

Lastly, the size of the guidance tunnel also affected pilot's performance (tunnel guidance was presented for all DC tested for the approach maneuver). For the given size of the tunnel (i.e. 400 ft wide by 320 ft tall), the guidance tunnel becomes larger then the glideslope beginning at approximately 600 ft AGL. By the end of the approach (i.e. 200 ft AGL), the tunnel was approximately 2.7 times (5.4 dots) as large as full-deflection of the glideslope. This visual cue could have contributed to the low-time pilots' apparent lack of awareness of large glideslope deviations, as presented by the glideslope error diamond. All of the approaches conducted by the low-time pilots produced maximum vertical deviations that remained within the tunnel boundaries (i.e. +/-160 ft) and yet exceeded glideslope tolerances.

Field of View

One objective of this flight test effort was to establish recommended FOV use for SVS GA applications. One factor affecting FOV use was the need to keep the velocity vector on the display. Significant crab angles were observed for both en route and approach maneuvers primarily due to the airspeeds employed (i.e. 100 kts and 90 kts). Cross wind conditions encountered were considered mild. In addition, turbulence effects, combined with the natural flight dynamics of the aircraft, produced substantial motion of velocity vector position. Occasionally, pilots were able to employ lower FOVs (30 degrees), to enhance their view of the runway during the latter stages of the final approach. However, due to the dynamics of the aircraft combined with the operating speeds, resulting measured FOVs typically ranged near 60 degrees. In post-block questionnaires, all pilots selected 60 degrees FOV as the most preferred for the approach maneuver. The average of most preferred FOV for the en route maneuver was 64 degrees. Therefore, the recommended FOV for SVS GA applications is 60 degrees. Removal of pilot-selectable FOV control may not impose substantial restrictions on the utility of these displays due to characteristics inherent to GA aircraft. This recommendation is counter to reference [2] that involved testing with large transport aircraft. However, lower FOVs, such as 30 degrees, could still be useful for calm operating conditions, providing increased utility during latter stages of final approach.

Concluding Remarks

SVS displays have the ability to provide enhanced terrain awareness. A continuing objective for SVS displays is the appropriate integration of SVS terrain with other elements of the display to provide optimum pilot SA and workload. Evidence is provided in this study to further substantiate the idea that high-resolution photo-realistically textured terrain databases and high-resolution digital elevation models may combine to detract from optimal pilot performance (due to the extreme level of detail provided by these types of SVS displays) for the maneuvers tested. However more data is required to draw final conclusions.

The use of color and texture, as employed for the elevation-based generic and photo-realistic texturing concepts, has the potential to greatly enhance pilot's terrain awareness over that provided by a constant-color with fishnet grid terrain portrayal or a standard blue-sky/brown-ground PFD. Low-time pilots were not capable of flying

ILS approaches to established IFR PTS criteria as indicated by their maximum glideslope and airspeed errors. However, enhancements in symbology (velocity vector dynamics and guidance tunnel size) and/or the addition of a tachometer could provide needed improvements. High-time pilots exceeded the IFR PTS criteria for ILS approaches as tested.

Field of view recommendations from this test indicated that 60 degrees was the most preferred for approach and would provide the most utility because of the substantial movements of the velocity vector typical in GA flight operations. Pilot selectable field of views, that include 30 degrees, could be beneficial in calm operating conditions on final approach.

Overall, a comprehensive evaluation of specific components (DEM/texture) of SVS terrain portrayal methods has been conducted through an extensive simulation and flight-test effort. Results indicated pilots were able to use the SVS displays effectively, with dramatically increased terrain awareness. In general, all SVS concepts tested provided similar results with some other study data [11] suggesting that ultimate terrain portrayal fidelity (photo-realism) might not be as important as effective terrain portrayal presentation (elevation-based generic). One potential concept that is recommended for further evaluations would be a hybrid EBG/Photo-realistic texturing method blending high-detail cultural and feature data with the easy to perceive elevation-based generic texturing. Such a hybrid concept could combine positive features from both texturing concepts.

Subsequent reports resulting from the TP-HDD test series will focus more fully on the remaining study objectives. Future work should address the issues of SVS terrain integration with a focus on the interactions between terrain fidelity, symbology, and useable FOVs.

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[14] FAA Instrument Rating Practical Test Standards

Figures

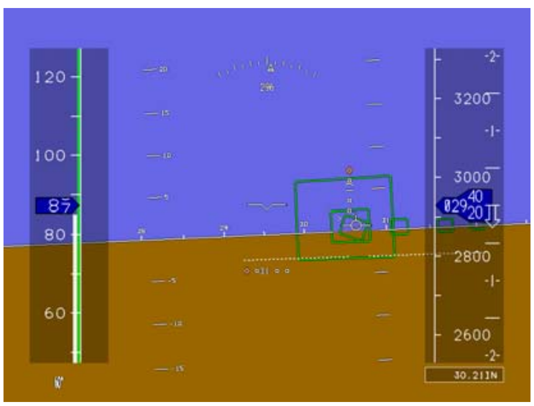

Figure 1. Blue-Sky Over Brown-Ground Baseline (DC 1) With All Symbology Elements

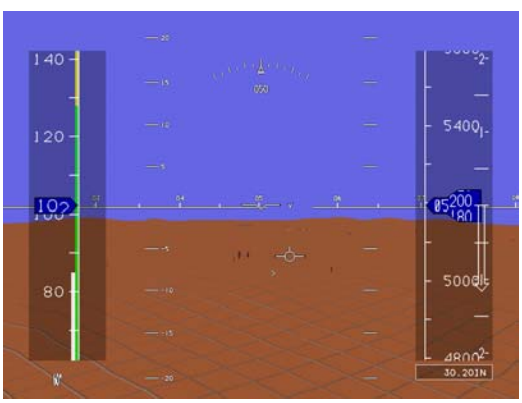

Figure 2. Constant Color Texture with Fishnet Overlay and 30-arcsec DEM (DC 2)

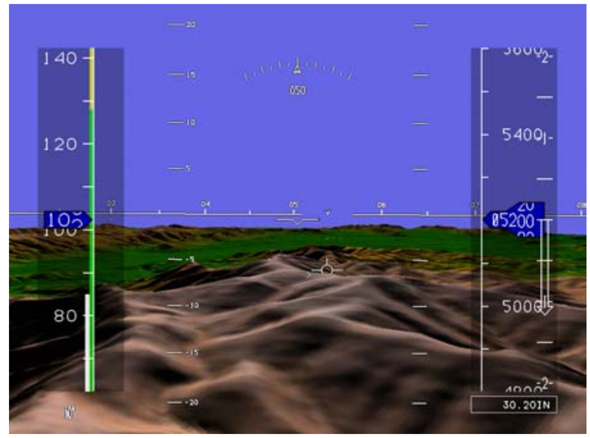

Figure 3. Elevation-based Generic Texture with 1-arcsec DEM (DC 4)

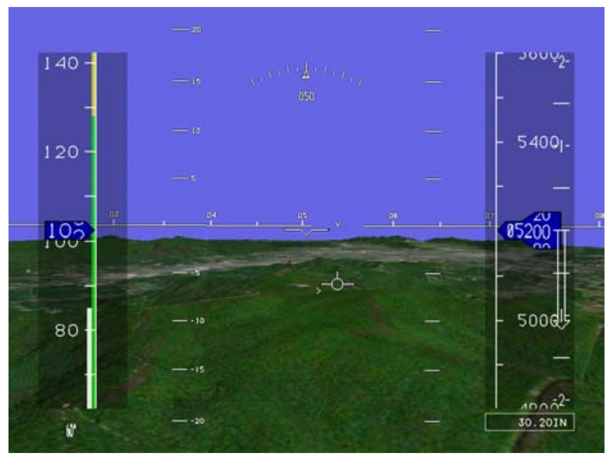

Figure 4. Photo-realistic Texture with 1-arcsec DEM (DC 6)

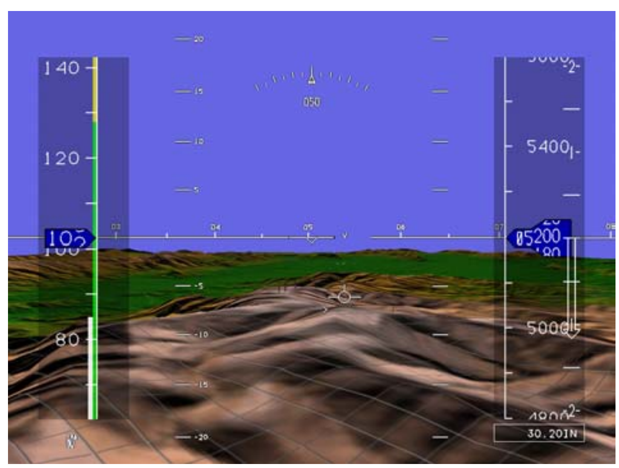

Figure 5. Elevation-Based Generic Texture with Fishnet overlay and 3 arc-sec DEM (DC 7)

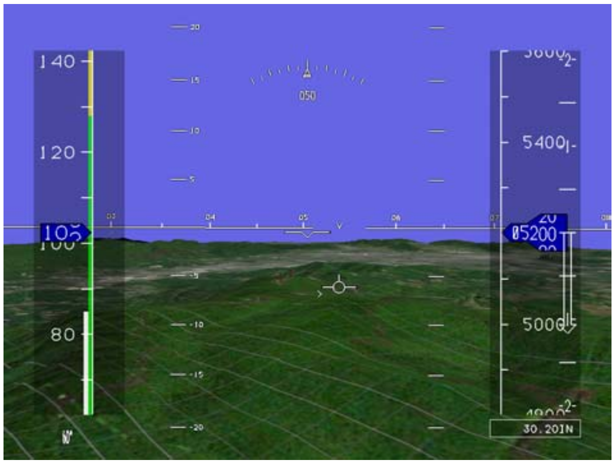

Figure 6. Photo-realistic Texture with Fishnet Overlay and 3 arc-sec DEM (DC 8)

Figure 7. Photograph of MX-20 during approach to Roanoke, VA.

Figure 8. Cessna 206-H Stationaire (NASA 504).

Figure 9. Experimental Instrument Panel During Final Implementation

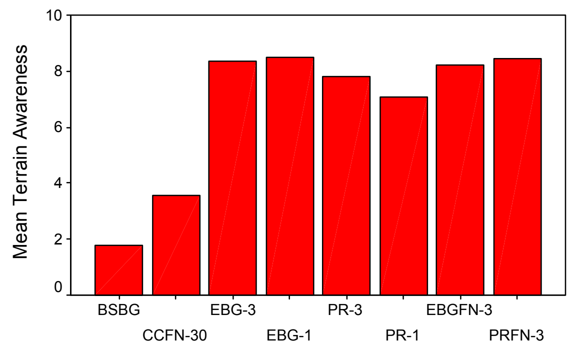

Figure 10. En Route terrain awareness for all DCs tested (0=no location-specific terrain awareness).

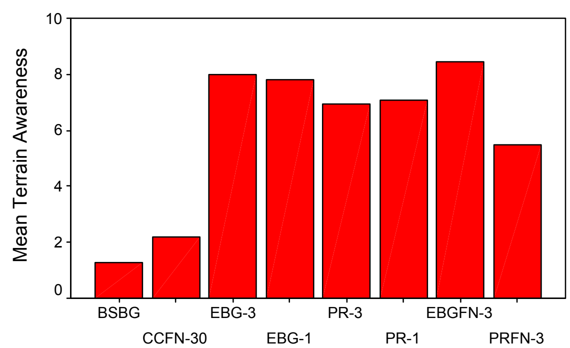

Figure 11. Approach terrain awareness for all DCs tested (0= no location-specific terrain awareness).

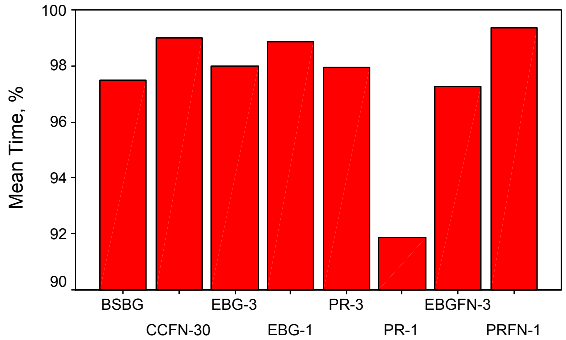

Figure 12. Percent time pilots maintained Level-1 performance for the entire En Route maneuver.

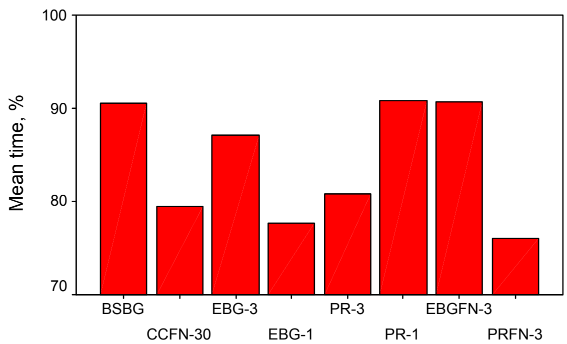

Figure 13. Percent time pilots maintained Level-1 performance during Segment 7 of final approach.

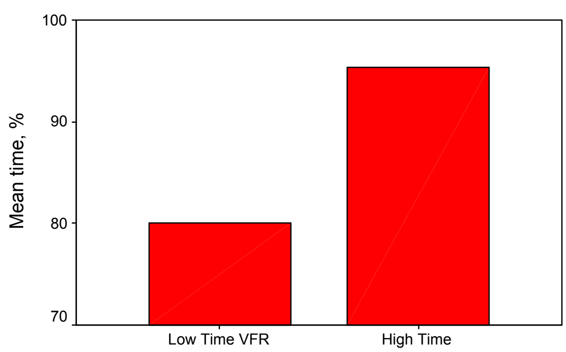

Figure 14. Percent time pilots maintained Level-1 performance for the entire approach task (averaged over all DCs).

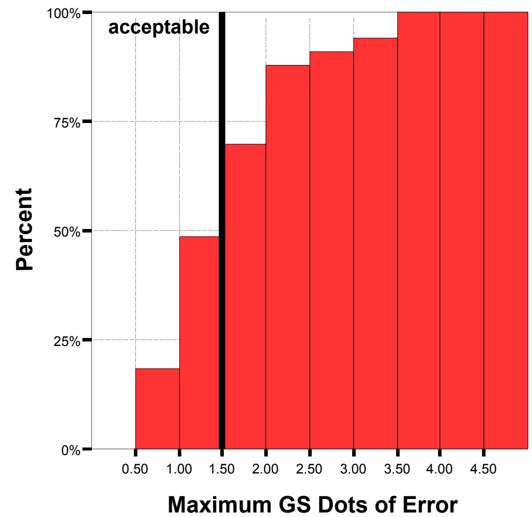

Figure 15. Histogram of Maximum Glideslope Error (averaged over all DCs) for Low-time VFR Pilots for Segment 7 of final approach.

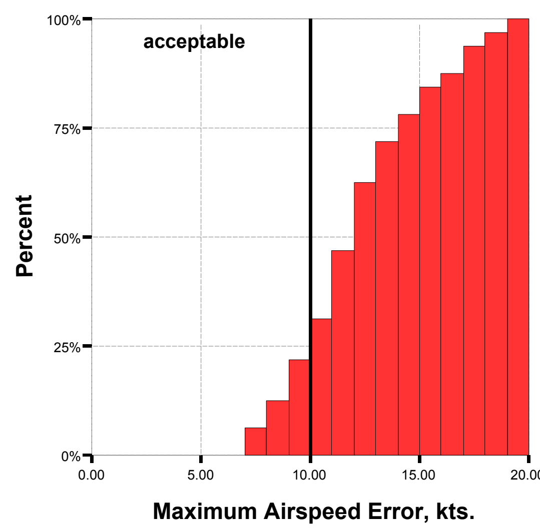

Figure 16. Histogram of Maximum Airspeed Error (averaged over all DCs) for Low-time VFR Pilots for Segment 7 of final approach.