

TERRAIN PORTRAYAL FOR HEAD-DOWN DISPLAYS EXPERIMENT

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Abstract

The General Aviation Element of the Aviation Safety Program's Synthetic Vision Systems (SVS) Project is developing technology to eliminate low visibility induced General Aviation (GA) accidents. SVS displays present computer generated 3-dimensional imagery of the surrounding terrain on the Primary Flight Display (PFD) to greatly enhance pilot's situation awareness (SA), reducing or eliminating Controlled Flight into Terrain, as well as Low-Visibility Loss of Control accidents. SVS-conducted research is facilitating development of display concepts that provide 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. An experimental study has been conducted at NASA Langley Research Center to explore and quantify the relationship between the realism of the terrain presentation and resulting enhancements of pilot SA and pilot performance. Composed of complementary simulation and flight test efforts, Terrain Portrayal for Head-Down Displays (TP-HDD) experiments will help researchers evaluate critical terrain portrayal concepts. The experimental effort is to provide data to enable design trades that optimize SVS applications, as well as develop requirements and recommendations to facilitate the certification process. This paper focuses on the experimental set-up and preliminary qualitative results of the TP-HDD simulation experiment. In this experiment a fixed based flight simulator was equipped with various types of Head Down flight displays, ranging from conventional round dials (typical of most GA aircraft) to glass cockpit style PFD's. The variations of the PFD included an assortment of texturing and Digital Elevation Model (DEM) resolution combinations. A test matrix of 10 terrain display configurations (in addition to the baseline displays) were evaluated by 27 pilots of various backgrounds and experience levels. Qualitative (questionnaires) and quantitative (pilot performance and physiological) data were collected during the experimental runs.

Preliminary results indicate that all of the evaluation pilots favored SVS displays over standard gauges, in terms of terrain awareness, SA, and perceived pilot performance. Among the terrain portrayal concepts tested, most pilots preferred the higher-resolution DEM. In addition, with minimal training, low-hour VFR evaluation pilots were able to negotiate a precision approach using SVS displays with a tunnel in the sky guidance concept.

Introduction

Synthetic Vision Systems (SVS) displays for General Aviation (GA) applications are designed to enhance pilot's situation awareness (SA), radically reducing the occurrence of Controlled Flight into Terrain (CFIT) accidents in addition to reducing or eliminating pilots' spatial disorientation (SD), thus preventing low-visibility induced Aircraft Upset (LVAU) events. LVAU events without recovery might lead to a Low Visibility Loss of Control (LVLOC) accident. Using imagery derived from terrain, obstacle, and airport databases, SVS displays provide the pilot with an unobstructed view of the outside terrain, regardless of weather conditions and time of day. In addition, through the integration of advanced symbology (i.e. highway in the sky, velocity vectors, etc.), navigation performance is drastically improved, with no effective increase in pilot workload.

The genesis of the Terrain Portrayal for Head Down Displays (TP-HDD) simulation experiment can be attributed to several factors. Actual requirements for terrain resolutions and texturing methods used to generate imagery on a PFD were previously undefined. In an attempt to utilize current technology

avionics platforms with limited computational power, industry SVS displays appear to be achieving substantial improvements in pilot performance over conventional displays. These new industry SVS displays utilize low to medium Digital Elevation Model (DEM) resolution databases (in the 30 arc-sec range) and simple terrain texturing concepts. At the time this paper was written, references were not available to document GA industry SVS performance improvements. In contrast, the RTCA (Special Committee 193 (SC-193) and EUROCAE Working Group 44 (WG-44)) have prescribed database resolution requirements intended to meet foreseeable aviation application that are much higher than current industry SVS applications. The RTCA committee recommends 3 arc-sec DEM for en route operations, 1 arc-sec DEM for terminal operations, and .3 arc-sec DEM for surface operations [1]. As a result, an inconsistency exists between GA industry SVS DEM data usage and the RTCA recommendations. In addition, there is a pervasive belief among various elements within the aviation community that high-resolution DEM data always provides significantly superior pilot SA and better pilot performance than lower-resolution DEM data. This belief is fueled, in part, by elaborate pictures of high-fidelity terrain portrayal SVS concepts. While higher fidelity terrain portrayals can be applied to SVS terrain displays, there is an inherent increase in SVS system complexity and cost. Previous SVS research has demonstrated that various concepts can work; however proportional benefits of high-fidelity SVS imagery were unknown prior to this effort. In-depth research to help define the terrain portrayal requirements for SVS displays is needed. The combined TP-HDD simulation and flight efforts explores these issues in order to attempt to generate critical data that will provide a basis of recommendations appropriate for all SVS applications, with a focus on GA.

While previous studies have been conducted regarding the understanding of SA and SD, leading to some novel concepts, only relatively minor progress has been made towards measuring the effectiveness of these advanced flight display concepts [2-8]. As an initial investigation, the SVS-GA team conducted a study that focused on determining the associated benefits of SVS displays towards reducing LVLOC and CFIT accidents for GA pilots [2]. Results of that fixed-based simulator study demonstrated the effectiveness of generic SVS displays as compared to conventional GA flight decks in reducing pilot errors and thus improving pilot ability to control the aircraft during IMC. The current study builds upon results from reference 2 in addition to evaluation of multiple SVS display concepts.

Objectives of the TP-HDD Experiment

One of the primary challenges of SVS as a PFD is the presentation of appropriate information in a cost effective and computationally viable manner. The TP-HDD experiments focus specifically on the aspect of portraying terrain on a PFD. As previously mentioned, the TP-HDD study consists of two distinct efforts. The first (current study) focused on flight simulation while the next phase of the study is planned to be a flight experiment, employing the NASA LaRC Cessna 206 research aircraft.

The objectives of the TP-HDD simulation experiment were to establish the relationship between terrain depiction fidelity and pilot's terrain SA, pilot's performance (control and navigation), and prevention of LVLOC /LVAU incidents. The final goal of TP-HDD was to further establish the overall benefit of SVS for GA pilots.

Upon completion of both simulation and flight experiment studies, results are expected to provide information to help establish the DEM resolution and texturing requirements for tactical HDDs, based on the phase of flight. Another anticipated outcome is to provide data to enable SVS design tradeoffs (performance vs. fidelity) and to develop integration of tactical HDDs with strategic terrain displays. In addition, this experiment directly provided support for the Federal Aviation Administration (FAA) Capstone-2 certification issues. The Capstone-2 program is endeavoring to develop and supply new and emerging avionics technologies to the commercial aircraft fleet in Juneau, Alaska, to reduce the extremely high-rate of aircraft accidents in that area. One technology being employed for Capstone-2 are SVS displays.

Method

The experiment was conducted using a fixed based simulator equipped with a strategic (navigation) and a tactical (primary) flight display. Various terrain portrayal concepts were developed from combinations of DEM resolutions and texturing concepts. These displays were evaluated in the General Aviation WorkStation (GAWS) facility at NASA Langley Research Center. Twenty-seven subject pilots participated in the TP-HDD simulation experiment.

Display Concepts

The display concepts evaluated can be grouped into three types. One type of display replicated conventional PFD's and was referred to as the blue-sky/brown ground (BSBG) concept. PFD's feature integrated information (i.e. airspeed, altitude, attitude) into one display (see Figure 1).

Another type of display employed for this test was referred to as the baseline round dials (BRD) and is shown in figure 2. The round dial concept replicates instrumentation currently found in the vast majority of GA aircraft.

The third type of display evaluated is referred to as the SVS display concept. SVS display concepts were identical to the conventional PFD, with the addition of the various SVS terrain portrayals in place of the blue-sky/brown-ground. Figure 3 is an example of one of these SVS display concepts, with the Photo Realistic (PR) texture and DEM = 1 arc-sec.

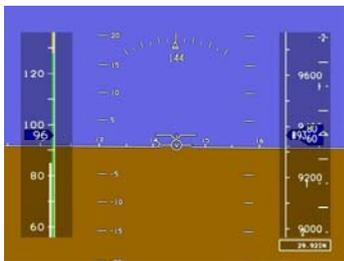


Figure 1. SVS BSBG
Baseline



Figure 2. C172 BRD

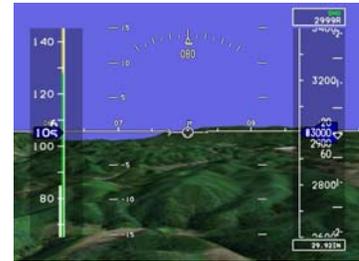


Figure 3. SVS Display
Concept with Terrain

Symbology

Primary Flight Display

The SVS PFD featured several advanced symbology elements, including air-data, orientation, and guidance information. Air-data information was presented by use of integrated airspeed and altitude tapes with a vertical speed indicator, including digital readouts of instantaneous values of indicated airspeed and altitude. A roll pointer with a sideslip wedge and magnetic heading digital read-out, and a pitch ladder portrayed heading and attitude orientation information. Additional symbology components displayed on the PFD were elements that characterized the velocity vector cluster. This cluster depicted current aircraft flight path angle and track angle, incorporating a non-quickened velocity vector with an acceleration-along-flight-path indicator (off the left finlet of the velocity vector marker) and sideslip flag (off the top finlet of the velocity vector marker). Guidance symbology was presented in the form of course deviation indicators showing glide slope and localizer deviation dots and a tunnel in the sky type of symbology (see Figure 4). The tunnel in the sky concept featured 420 feet wide by 320 feet tall, uniform green boxes depicting the current flight path for the approach scenario, providing lateral and vertical path guidance. Vertical and lateral path deviation indicators provided the pilot with information regarding proximity of the aircraft to the center of the tunnel.

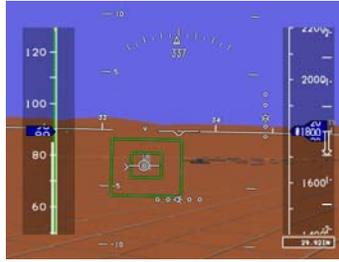


Figure 4. Example of the Constant Color with Fish Net, DEM =30 arc-sec, with Tunnel

Strategic Display

SVS perspective displays are designed to provide pilots with terrain SA similar to and beyond the information provided by strategic terrain display concepts, such as the United Parcel Service Aviation Technologies (UPSAT) MX-20 multifunction display (MFD) (UPSAT MX-20). 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 (see Figure 5), and was located in the radio stack. On the MX-20 MFD, terrain awareness, route information, waypoints, and towers were portrayed. All display concepts, including both baselines, were evaluated in the presence of the MX-20 MFD.

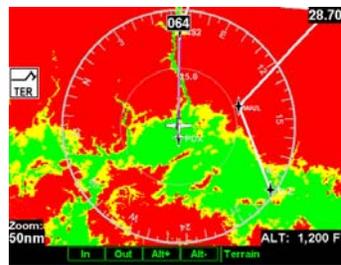


Figure 5. MX-20 MFD in Terrain Awareness Mode

Terrain Databases

Enclosing the Roanoke Regional Airport (KROA), the simulated area of operations, termed the ROA Sector, was located in a relatively mountainous area in Virginia (VA), and was defined by the boundaries of 37° 30'N, 79° 40'W, 37° 00'N, and 80° 40'W. The SVS display concepts developed were combinations of various Digital Elevation Model resolutions (from the ROA Sector) and terrain texturing concepts.

Digital Elevation Model resolutions: DEM resolution defines the distance between elevation data points (post-spacing) for a given a given database. A low resolution, 30 arc-sec (900m/2953ft post-spacing) DEM, a medium resolution, 3 arc-second (90m/295ft post-spacing) DEM, and a high resolution, 1 arc-sec (30m/98ft post-spacing) DEM, were investigated in this experiment. These three DEM resolutions were chosen with the intent of covering a broad range of viable DEM options. Specifically, the 30 arc-sec DEM is currently used by the industry and is a freely available database. The 1 arc-sec and 3 arc-sec DEMs are part of the set of DEMs prescribed by the RTCA and form an upper bound for current consideration.

DEM resolution specifies the post-spacing of the elevation data points. It should be noted that the higher resolution databases are larger in terms of overall data points for a given area of coverage, thus higher computational expenses are associated with manipulating these data. Since the databases for the

lower resolutions are less populated than the higher resolutions, substantial terrain features might potentially be excluded. The possibility of losing entire peaks in the lower resolutions, as well as detailed terrain relief, exists. In Figure 6, a “rounded” effect becomes apparent between the DEM=3 and the DEM=30 (refer to the area indicated by the arrows in Figure 6). For this example, the elevation-based generic texturing concept is employed.

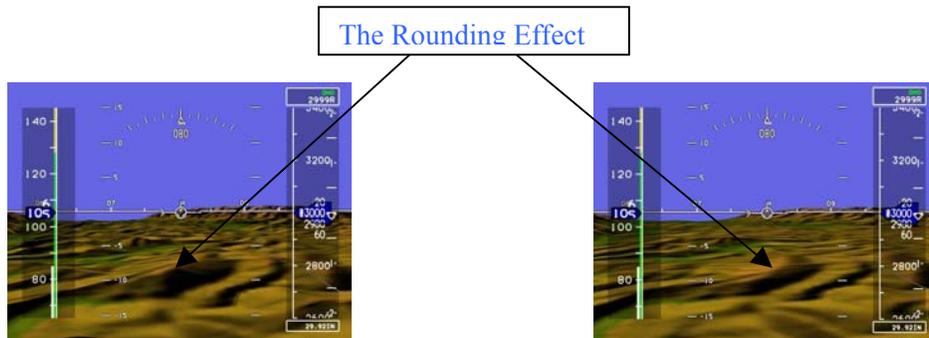


Figure 6. Difference between DEM = 3 (left) and DEM = 30 (right)

Terrain-Texturing Concepts: Terrain-texturing refers to the method used to enhance elevation cues and position estimates of the DEM 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 replicate a current industry concept that is in the process of Federal Aviation Administration (FAA) certification for the Capstone-2 program. This texturing concept represents a minimal SVS display concept requiring a nominal amount of computational resources for rendering available from current certified avionics platforms. The elevation-based texturing concept consists of different coloring bands that correspond to different absolute terrain elevation levels. Lower terrain levels are colored with darker colors, and higher terrain levels are assigned lighter colors. A certain shade of green was set to the field elevation, and the highest point was set to the highest terrain within 50nm of ROA, approximately 4,000 ft MSL. The photo-realistic texturing was derived from 4m satellite imagery data that was draped over the various DEM databases. For the CC and EBG terrain texturing display concepts, cultural features, such as roads, towers, and rivers, were presented on the display. Cultural and feature data were supplied directly through the photo-texture images on the PR display concept.

Fishnet (FN) Overlay Concept: In addition to primary terrain texturing concepts, a fishnet grid overlay was employed. The theory of the fishnet grid involves placing grids of known sizes within the synthetic scene to facilitate pilot’s depth perception. The potential benefits of the fishnet grid used in this study are cues for depth perception, distance, and angular rates. In addition, this fishnet grid provided a constant geometric shape in the synthetic terrain scene. However, the fishnet grid may introduce elements of confusion in terms of adding to display clutter, distracting the subject pilot, and being mistaken for the roads and rivers. These types of issues were investigated in this experiment. The spacing of the fishnet overlay was 500ft by 500ft, regardless of the DEM resolution. The grid was dual-color (gray/white), to compensate for different coloring of features within the terrain databases (i.e., lighter colors of populated areas for the PR texture).

Test Matrix

Combinations of DEM and texturing concepts (including the FN option) produced 18 different potential terrain portrayal concepts to evaluate. A preliminary look at these 18 display concepts revealed that the CC texture without a FN provided little evident information on terrain contouring. As a result, the CC texture without the FN was eliminated as a viable concept for terrain portrayal. For the remaining

15 concepts, a usability study was then conducted in order to down-select a smaller and more manageable set of candidate display combinations for more thorough investigation. While the formation of this set of candidate display concepts was based on subject pilot evaluations, the suggested collection of display concepts was broad enough to meet the objectives of the experiment. Subsequently, an adequate number of display-concepts (10) were retained for the core experiment (see Table 1).

Table 1. TP-HDD Experiment Matrix (Legend: EBG=Elevation-Based Generic, PR=Photo Realistic, CC=Constant Color, FN=Fish Net)

Texturing Concepts						
DEM (arc-sec)		EBG	PR	CCFN	EBGFN	PRFN
	30			√	√	√
	3				√	√
	1	√	√	√	√	√

These 10 SVS concepts were evaluated in addition to the specific baseline concept flight displays mentioned earlier. These two baseline flight displays, BSBG and BRD were split evenly between subject pilots with specific qualifications. All display concepts were randomized among the pilots, for each maneuver.

One additional run was added to the above matrix for one specific texturing concept (Constant Color with Fish Net) and particular DEM (30 arc-sec), but without a tunnel during the approach maneuver. This trial was included in order to establish pilot performance and workload relationships regarding use of the tunnel in the sky guidance concept.

Evaluation Pilots

Twenty-seven evaluation pilots of various backgrounds and qualifications participated in the TP-HDD simulation and were grouped by certain characteristics. The first group of subjects consisted of fourteen low-time pilots with less than 400 hours and no instrument training beyond that required for the private pilot’s license rating. Six Instrument Rated pilots with various levels of experience, but less than 1000 hours, made up the second set of subjects. The last group of evaluation pilots consisted of four professional test pilots from NASA and the FAA and three Juneau (Alaska) area commercial operators. The Juneau pilots are potential future Capstone II users.

Simulation Equipment

The GAWS facility platform is based on a modified Precision Flight Control PC-based Aviation Training Device (PCATD) Model PI-142 instrument procedure trainer (see Figure 7). The model PI-142 uses hardware typical of a general aviation aircraft with left- and right-pilot seats. Modifications to the hardware included the addition of a 6” SVS-PFD and a UPSAT MX-20 MFD.

Additionally, three different computers were employed to drive the system in GAWS. One computer, a Pentium-3 class PC, hosted the Initiative Computing (IC) Elite Electronic IFR Training Environment Version 6.2 software. This Elite software provided the aircraft dynamic responses to pilot control inputs, and control of the out-the-window weather, as well as data required to generate the research display imagery. Elite software can simulate various types of GA aircraft including a generic Cessna-172 model, which was used in this experiment. A Silicon Graphics Zx10 PC with a 3Dlab WildCat 4210 graphics card housed the SVS software employed to render the display presented on the SVS-PFD. This SVS display software included the underlying databases with the various DEM resolutions and texturing concepts, combined with the SVS symbology. The third computer, another

Silicon Graphics Zx10 PC with a 3Dlab WildCat 4210 graphics card, hosted the software that produced the out the window visual that was projected on the forward screen, to simulate the out the window view.



Figure 7. The General Aviation Workstation Facility Configured for TP-HDD

A pilot-selectable Display Field of View (FOV) control was developed for the experiment. Field of View is defined as the horizontal FOV of the image presented on the display. The four FOV choices for this experiment were 22°, 30°, 60°, and 90°. A minification factor (MF), which is the amount of angular compression to force an image to “fit” onto the display, is associated with each FOV. As the horizontal FOV increases, so does the MF. Higher MFs make terrain features appear further away than they are in reality. Two control options were available to the subject pilots, one located on the left-hand side of the instrument panel and one positioned on the right horn of the yoke. Previous research data indicate that a single fixed FOV would significantly limit SVS effectiveness. While flying each of the evaluation tasks, the subject pilots were encouraged to scroll through the FOV options during each phase of flight, evaluate the options, and provide comments during this experiment, as well as supply a resulting FOV strategy at the completion of the experiment.

Evaluation Tasks

The evaluation tasks were developed to cover critical phases of flight. En route and approach phases of a flight were ranked as high priority for SVS applications by an earlier in-house study describing the SVS Concepts of Operation for GA [9]. To add some additional sensation of realism and more representative levels of workload, a low/moderate level of turbulence was simulated throughout the experiment.

En Route:

The en route task required the evaluation pilot to maintain assigned heading, airspeed, and altitude values at different points during a 5-minute flight simulation. Each task began 19nm southwest of the Roanoke Regional Airport (ROA), with a heading of 140° and an airspeed of 100 KIAS. The high altitude en route task was initiated at 9,500 ft MSL (approximately 7,000ft AGL), while the low altitude en route maneuver began at 6,500 ft MSL (approximately 4,000 ft AGL). For both tasks, 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 evaluation pilots were asked to execute left turn, using 20 degrees of bank, to a heading of 050°, while simultaneously descending 1500 ft (over rising terrain). For this maneuver, part of the descent took place during the 90°-turn, while the rest of the descent was completed while maintaining the second target heading. The target level-off altitude for the high altitude task was 8,000 ft MSL (approximately 4,000 ft AGL), while the target altitude for the low altitude task was 5,000 ft MSL (approximately 1,000 ft AGL). At the starting

point of the maneuver, Visual Meteorological Conditions (VMC) was simulated. One minute into the flight a one-minute transition into Instrument Meteorological Conditions (IMC) was simulated by reduction of visibility on the out of window visual display to one statute mile. High altitude and low altitude maneuvers were chosen to examine the effectiveness of visual differences in the research terrain database at higher versus lower altitudes and to more comprehensively cover the GA operational envelope.

Instrument Approach:

The approach task consisted of a 6.5-minute flight simulation starting with a straight and level flight in VMC on a 30-degree localizer intercept course for the ILS 33 approach into ROA. The task started 12 nm south of ROA at 2,600 ft MSL, with a speed of 90 KIAS. The subject pilots were tasked to fly a heading of 300° to join the localizer (approximately 10 nm from the threshold) and maintain 2,600ft until intercepting the glide slope at approximately 4.5 nm, then continue flying the approach to 200 ft AGL. In this case, out of window visibility was reduced from VMC to one statute mile within the first minute of the flight. In addition to moderate turbulence that decreased throughout the run, wind was simulated to be from 030° at 15 kts, decreasing to 5 kts on final. One objective of the instrument approach maneuver was to demonstrate that non-instrument rated pilots are able to fly to an acceptable level of precision, with minimal training, using an SVS PFD with tunnel symbology.

Rare Event:

The Rare Event task simulated a flight scenario with an incorrect altimeter setting. Effectively, the altitude tape indicated the incorrect (higher) altitude, which was different from the actual altitude portrayed by the terrain on the PFD. In addition, the altitude provided by the MX-20 also included the 1,500 ft error. This task was administered at the very end of the data collection for each evaluation pilot and was designed to look like the low altitude en route task. The starting point was at the same position as the low altitude en route task, but actual altitude was 1500 ft lower. Consequently, the target level-off altitude for this maneuver was 500 ft below ground level. Display concepts, excluding baseline concepts, were randomized among pilots, repeating one of the display concepts the evaluation pilot had already flown. The purpose of the rare event was to provide a good experimental evaluation to determine whether or not the different SVS terrain concepts on the PFD provided enough improved terrain situation awareness to avoid CFIT accidents in a rare event.

Operations

The experiment was conducted within a 2.5 month–duration with no schedule interruptions. Each pilot participated in a day and a half of testing, consisting of approximately 35 trial runs, and 945 total trial runs for all pilots. Before the start of the experiment, each pilot received an extensive pilot briefing, as well as approximately one-hour of training time in the GAWS by a FAA certified flight instructor for instruments (CFII). The goal of these briefings and training was to familiarize each subject with the objectives of the experiment and educate the subjects on the salient features of the current SVS symbology set and the simulator functionality. The symbology set remained consistent across terrain databases and phases of flight, except for the tunnel-on and -off concepts. All high altitude trials were completed during one block of 11 runs; all low altitude trials were completed during the next block of 11 runs; and all approaches were completed in the third block of 12 runs. As previously stated, the rare event was typically the last run of the experiment for each subject pilot.

Data Description and Analyses

An exceptionally large amount of data has been collected for this experiment and detailed data analyses are in progress. The intent of this section is to describe the methodology of data collection, as well as describe the methodology used to analyze the data. A comprehensive report of the results of the experiment will be completed in the near future.

Quantitative Data

Pilot Performance

Pilot performance and control inputs for all flight conditions (68 parameters) were recorded at 30 HZ. Both the en route and the approach maneuvers were manually subdivided into 7 different segments using custom-developed software. Figure 8 depicts the segmentation methodology specific to the approach maneuver, focusing on the MSL Altitude and roll angle data for one particular pilot. For the approach, the maneuver began with straight/level flight on a 30° localizer intercept course (segment 1), transitioning to the turn maneuver to capture the localizer (segment 2), the actual turn with a constant bank angle (segment 3), transitioning to straight/level flight on the localizer course (roll-out)(segment 4), straight/level flight tracking the localizer (segment 5), transitioning to descent and glide slope capture (segment 6), and the final descent portion of tracking localizer and glide slope (segment 7).

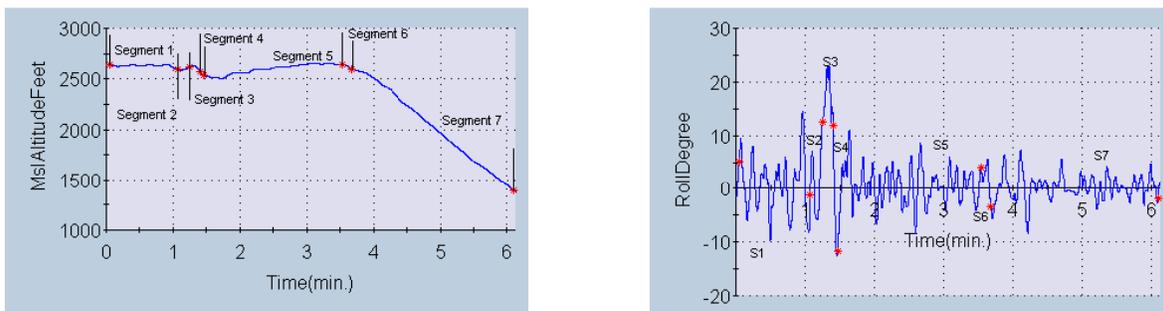


Figure 8. Segmentation of a Scenario for the Approach Maneuver, Segment 1 - Segment 7 (S1-S7)

One of the pertinent parameters in measuring pilot performance during an approach maneuver is the computed lateral and vertical path deviation (in feet). As a sample, Figure 9 shows the time history of these two parameters for the same evaluation pilot as the data shown in Figure 8, during the same run.

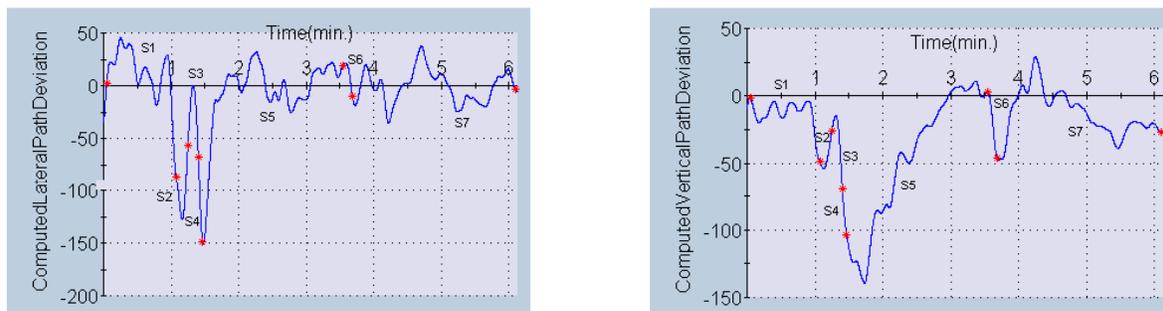


Figure 9. Lateral and Vertical Path Deviation for a Typical Approach Maneuver

Minimum, maximum, RMS, and standard deviations from target values of variables were computed for all pilots, scenarios and segments. This information then was cataloged into a spreadsheet which also included the run number, FOV, etc. The above information is then the basis for statistical post processing of the data using statistical analysis programs such as SPSS®.

Physiological Data

The following types of physiological measurements were conducted: heart-rate (sensors bracketing the heart), skin temperature (a sensor on the right ring finger), and muscle response (sensors on the left fore-arm). Physiological data was collected for all pilots during the approach tasks and for the final four subjects during the rare event task.

Qualitative Data

Pilot Comments

Subject pilot comments were recorded real-time during each run, after each block, and during the final semi-structured interview, via the audio and video recordings. Over 216 hours of multi-media recordings were compiled. The multimedia recordings allow the researchers to determine what each evaluation pilot was experiencing, real-time, while dynamically working with each display concept. All evaluation pilot comments and remarks will be transcribed and analyzed.

Post-Run Questionnaires

A post-run questionnaire was administered at the completion of each trial run. The post-run questionnaires consisted of three types of activities: Situation Awareness Rating Technique (SART), NASA Task Load Index (TLX), and Cooper-Harper rating scale. A SART is a situational awareness subjective measure. The NASA-TLX is used to analyze pilot's mental workload. The Cooper-Harper rating scale was administered in an attempt to determine pilots' perception as to whether or not the different display concepts affected the handling characteristics of the simulated aircraft model, as well as provide a means to bench-mark the simulation facility with the actual flight test aircraft.

Block Questionnaires

After each maneuver block, a block questionnaire was administered. This questionnaire consisted of the SA-Subjective WORKload Dominance (SWORD, see below) Technique, text questions regarding subject pilot FOV strategy, performance and terrain awareness ratings for each display concept, and general questions about the use of the primary and strategic flight displays.

The SA-SWORD was developed by Vidulich and Hughes [8]. Using the SA-SWORD, the subject pilots were asked to compare one display concept versus another, in a pair-wise comparison (across all display concepts), using a nine-point scale. These comparisons, for each pair of display concepts, indicate the subject pilot's determination of the level of SA enhancement one display concept may provide over another display concept.

Semi-Structured Final Interview

At the completion of each subject pilot's experiment, an exit interview was conducted. The interviews focused on verbal and visual protocols to elicit participant responses. These interviews were flexible to draw upon comments from each facet of the experiment.

Initial Results

Sample Quantitative Results:

Throughout the entire experiment, a trend emerged indicating that the subject pilots were experiencing various levels of stress when coming into close proximity with terrain during the rare event maneuver. As a result, the decision was made to collect physiological data on the remaining four evaluation pilots, during the rare event task. Data collection began after the evaluation pilot completed the turn to the target heading (about 3.2 minutes into the run). As an example of physiological data, Figure 10 illustrates the heart-rate data during the rare event scenario, averaged over the four subject pilots. Of interest on this particular graph is the amplification in heart rate, which occurred close to the end of the scenario. As the evaluation pilots flew closer to the terrain, their heart rate increased, suggesting that even though this was a simulation, conditions were realistic enough to induce some level of stress during this maneuver.

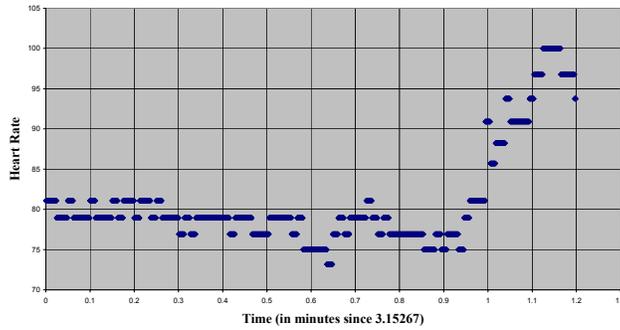


Figure 10. Average Heart-Rate During Rare Event Task

Qualitative Results:

The SA-SWORD data were calculated and a statistical ANOVA analysis was employed to determine if the findings were statistically significant. Specifically, terrain texture types (EBG, PR, and CC) were investigated, and the findings indicated that texture preferences were statistically significant ($F(2,759)=126.136, p<.001$). Further analysis revealed that, according to a Student-Newman-Keuls (SNK) Post Hoc test, no difference was detected in SA ratings between the PR and EBG texturing. However, a difference was evident between these two texturing types (PR and EBG) and the CC texture. The SA-SWORD data were also analyzed in reference to DEM resolution comparisons ($F(2,759)=188.037, p<.001$), revealing a statistical significance. SNK Post Hoc test results demonstrated that three distinct groupings existed, DEM=1, 3, and 30. As DEM resolution decreased, so did the subject SA-SWORD rating. This finding supported subject pilot comments indicating that SA was improved using DEM = 1 versus DEM=3, as was the case between DEM = 3 versus DEM = 30. And, finally, the use of the FN overlay, versus no FN overlay, in terms of enhancing situation awareness was not statistically important. More in-depth statistical analyses are in progress.

Table 2 illustrates a rank order of all display concepts (including each pilot’s respective baseline), based on subject pilot preference. This particular pilot preference data was compiled during the final interview. Pilots were asked rank the order the display concepts they would prefer to have in their aircraft for an approach task. The table nomenclature is as follows: texture, Fish Net (if applicable), DEM. For example, EBGFN30 is the elevation-based generic texture, with a Fish Net, DEM = 30 arc-sec. The ranking structure is 1-11 with 1 being the highest score.

Table 2. Subject Pilot’s Rank Order During Approach

Rank			
1	EBG1	7	EBGFN30
2	PR1	8	PRFN30
3	PRFN1	9	CCFN1
4	EBGFN1	10	CCFN30
5	EBGFN3	11	Baseline
6	PRFN3		

This ranking indicates that during an approach, the most preferred terrain portrayal concept was EBG1. While CCFN30 was the least preferred texturing concept, by far, the evaluation pilots overwhelmingly preferred this concept to either the traditional gauges or the BSBG baseline. The above qualitative results may support a pervasive belief among various elements within the aviation community

that high-resolution DEM data always provides significantly superior pilot SA and better pilot performance than lower-resolution DEM data. However, the results of the quantitative data will show if comparable SA and pilot performance can be achieved with lower resolution concepts.

Concluding Remarks

One of the primary challenges of Synthetic Vision Systems as a Primary Flight Display is the presentation of appropriate terrain information, in a cost effective and computationally viable manner. An experimental capability was developed to address some of these terrain portrayal concept issues. While only initial results were discussed in this paper, an attempt was made to focus on the methodology of the experiment and analyses tool developed. Three blocks of pilot performance data (68 parameters) were collected for the 27 pilots, and run questionnaires were administered after every trial for each pilot, totaling 945 runs of collected data. Physiological data were recorded during the approach runs for each pilot, in addition to the four runs collected during the rare event tasks, creating 328 physiological data sets for analysis.

Initial results strongly indicate that SVS displays with terrain depiction greatly enhance pilot situation and terrain awareness, and increase perceived pilot performance, without impacting pilot workload. In addition, with minimal training, low-time VFR pilots demonstrated the ability to execute precision approaches while using displays equipped with a tunnel in the sky guidance. More complete investigations are required before final conclusions are made on the interpretation of these data.

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