

Development and Evaluation of 2-D and 3-D Exocentric Synthetic Vision Navigation Display Concepts for Commercial Aircraft

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ABSTRACT

NASA's Synthetic Vision Systems (SVS) project is developing technologies with practical applications that will help to eliminate low visibility conditions as a causal factor to civil aircraft accidents while replicating the operational benefits of clear day flight operations, regardless of the actual outside visibility condition. The paper describes experimental evaluation of a multi-mode 3-D exocentric synthetic vision navigation display concept for commercial aircraft. Experimental results evinced the situation awareness benefits of 2-D and 3-D exocentric synthetic vision displays over traditional 2-D co-planar navigation and vertical situation displays. Conclusions and future research directions are discussed.

Keywords: Synthetic vision, exocentric displays, situation awareness, safety, controlled-flight-into-terrain, workload

1. INTRODUCTION

A "synthetic vision system" is an electronic means of displaying the pertinent and critical features of the environment external to the aircraft through a computer-generated image of the external scene topography using on-board databases (e.g., terrain, obstacles, cultural features), precise positioning information, and flight display symbologies that may be combined with information derived from a weather-penetrating sensor (e.g., runway edge detection, object detection algorithms) or with actual imagery from enhanced vision sensors. Synthetic vision systems may be shown on head-down, head-up, helmet-mounted, and navigation displays and be combined with runway incursion prevention technology; database integrity monitoring equipment; enhanced vision sensors; taxi navigation and surface guidance maps; advanced communication, navigation, and surveillance technologies; and traffic and hazard display overlays. What characterizes the Synthetic Vision Systems technology is the intuitive representation of visual information and cues that the pilot or flight crews would normally have in visual instrument conditions. However, synthetic vision is not simply an aide or adjunct to human visual perception, but rather integrates many technologies that together meet, or exceed, human capabilities found during visual rules flight.

1.1. NASA Synthetic Vision System Project

NASA's Synthetic Vision Systems (SVS) project is developing technologies with practical applications that will help to eliminate low visibility conditions as a causal factor to civil aircraft accidents while replicating the operational benefits of clear day flight operations, regardless of the actual outside visibility condition. The SVS concept being developed at NASA encompasses the integration of tactical and strategic Synthetic Vision Display Concepts (SVDC) with Runway Incursion Prevention System (RIPS) alerting, real-time terrain database integrity monitoring equipment (DIME), and Enhanced Vision Systems (EVS) and/or improved Weather Radar for real-time object detection and database integrity monitoring.

1.2. NASA Research on Synthetic Vision System

NASA has conducted a significant amount of commercial and business aircraft research on system components to support each of the synthetic vision system elements described above. Flight test research has been conducted at Asheville, NC (AVL), Dallas Fort-Worth (DFW), Eagle County Regional Airport (EGE), Wallops Island (WAL), and Reno, Nevada (RNO) (Glabb et al., 2003; Kramer et al., 2004, 2005). Without exception, the results consistently demonstrate the superiority of synthetic vision to improve flight path control performance, lower mental workload, and enhance situation awareness (SA) under varying weather and operational conditions. The flight test experiments have been supplemented by extensive simulation testing which have considered many human factors issues. This body of

research includes a significant amount of data collected on sensors, database, and alert and warning system components that are essential parts of the NASA synthetic vision system.

A key objective of the NASA synthetic vision system project is to pursue the design and development of advanced revolutionary cockpit system displays that will help to eliminate low visibility as a causal factor in accidents, including “forward-fit” applications. During previous simulation and flight testing, usability and post-experimental pilot comment data evinced the need for enhancements to the strategic, navigation display that might allow pilots to utilize and take advantage of the unique feature that synthetic vision provides --- presenting a 3-D visual analog of the outside world. To achieve this capability, synthetic vision would be presented on multiple displays, both in egocentric and exocentric display formats. However, there are a host of human factors to be considered (described in Section 1.3). The NASA Synthetic Vision System project has addressed many of the most significant problems found with egocentric primary flight displays and has reported many positive findings proving the efficacy of these displays for commercial aviation. The SVS project has initiated a research and development effort evaluating the use and utility of synthetic vision strategic navigation display concepts, including the use of multiple 2-D and 3-D exocentric display modes.

1.3. 3-D Synthetic Vision Navigation Displays

The combination of synthetic terrain presentation coupled with advanced guidance symbology has been shown to significantly enhance situation awareness, lower workload, and reduce flight technical error (e.g., Kramer et al., 2004; Prinzl et al., 2004). However, NASA research has shown these advantages over traditional cockpit displays for an egocentric synthetic vision primary flight display only. Although a recent flight test evaluated a synthetic vision 2-D “gods’-eye view” navigation display, there was not a direct assessment of the benefits, if any, of presenting synthetic vision using this 2-D co-planar format. This 2-D SVS strategic display was used as a demonstration, creating what seemed to be a direct enhancement to a present-day co-planar navigation display with a Terrain Awareness Warning System and a Vertical Situation Awareness display.

Although past research has consistently shown the superiority of synthetic vision egocentric displays compared to traditional primary flight displays, it remains to be seen whether the same is true for exocentric navigation displays. The human factors issues involved in exocentric displays are many. Below is a summary of these issues followed by a discussion of local guidance and global situation awareness and how these may be supported by exocentric synthetic vision displays. The use of the terms “2-D” and “3-D” pertain in the context of display drawing techniques, such as perspective, used to convey depth or “z-axis” information to the user. The 3-D display concepts presently considered in this research are not created using stereoscopy nor are stereoscopy artifacts included in this discussion.

1.3.1. 3-D Display Advantages. The nature of the pilot’s task dictates whether 2-D or 3-D displays should be used. Three-dimensional displays have been found to best support integration of information across several spatial locations into one display source so as to reduce the amount of visual scanning and mental integration required. Wickens, Merwin, and Liu (1994) found that subjects who viewed complex 3-D data sets were better able to answer questions regarding integration across sets but that focused attention was less well supported. Another advantage of 3-D displays relates to the concept of “pictorial realism” through the presentation of a view that is closer to what the pilot would expect to see if he or she was looking outside the cockpit window.

1.3.2. 3-D Display Disadvantages. Although 3-D displays have advantages in terms of integration and realism, there are potential costs associated with the use of these displays. First, 3-D displays suffer from “3-D-to-2-D project effect” (McGreevy & Ellis, 1986), or line-of-sight ambiguity, caused by depicting a 3-D scene on a 2-D screen resulting in ambiguity along the line of sight. For any given 2-D point there are an infinite number of 3-D positions with the display resulting in a reduction in depth cues available (e.g., Wickens, Todd, & Seidler, 1989). Furthermore, McGreevy and Ellis (1986) showed that, if additional depth cues are presented, foreshortening (slant overestimation) and resolution loss became issues. Foreshortening creates a “perceptual rotation” of the perceived display scene making objects appear closer than they really are. McGreevy and Ellis (1986) noted that, “this effect can promote overestimation of vertical separations, and will be worsened by increased scaling of the altitude dimension” (p. 455). Resolution loss, on the other hand, refers to the phenomenon where a change in position of depth results in a much smaller change in visual angle compared to a change in position of lateral or vertical separation. As Wickens et al. (1994) describe, “distances orthogonal to the line of sight are represented with greater pixel resolution than those more parallel to the line of sight” (p. 5). Resolution loss can result in inaccurate positioning of the object (e.g., ownship symbol), degrading depth perception and the perception of the natural horizontal and vertical position of objects located on the far edges of the 3-D

display as judged from the pilot's viewpoint. Finally, 3-D display may reduce the ability of the pilot to focus on an individual axis of information because of the integrative nature of the display.

1.4. Human Factors Design Considerations. There are several human factors considerations in the design of 3-D displays. Consider, for simplicity, that a pilot's task can be conceptualized as solely requiring local guidance and global situation awareness knowledge. Local guidance requires knowledge of current position relative to a specified ideal flight path whereas global situation awareness refers to knowledge a pilot has regarding potential hazards, future states and goals, etc. In other words, local guidance embodies the "where am I at now" characterized by what is typically seen in the pilot's forward field-of-view and is thus, best supported by a 3-D small-scale, egocentric frame of reference. Global situation awareness, however, requires a more world-centered frame of reference and requires knowledge that may not be present in the pilot's forward field-of-view and this is best supported by a larger-scale, exocentric frame of reference. These display frames-of-reference and the pilot's information needs are critical in the development of cockpit display design and layouts. The choice of egocentric or exocentric perspective, tethered length of viewpoint, elevation angle, planar or perspective view, and geometric field-of-view can modulate information processing and how pilots use the display for local guidance and global situation awareness.

1.5. Past Research and SVS Exocentric Displays

The sections above described research conclusions which make evident that 3-D exocentric displays have identifiable human factors shortcomings. What has not heretofore been considered are the effects of exocentric displays as part of a suite of displays which may have different display formats. Many research conclusions, such as those presented above, are based on experimental studies using single display concepts. It is questionable whether these sweeping generalizations mirror the real world in which a cockpit has multiple displays capable of presenting varied display formats.

While cognizant that an exocentric synthetic vision navigation display by itself may suffer from human factors issues (Section 1.3), this research is directed toward a tactical and strategic display combination such as whether synthetic vision, presented as an egocentric primary flight display, may complement an exocentric navigation display with or without synthetic vision. The question also logically turns to whether the addition of synthetic vision provides performance and/or situation awareness enhancement when presented on a navigation display? If so, what is the best way to design a synthetic vision navigation display? Because many of the limitations of exocentric display owe to their fixed viewpoint, another question is whether a multi-mode SVS navigation display presents a solution to the many human factors problems reported by earlier studies? To answer these empirical questions, an experiment was conducted that compared two SVS navigation display concepts to a traditional 2-D co-planar (baseline) navigation display (each paired with both SVS and non-SVS primary flight displays), and evaluated flight path performance, workload, and situation awareness during approach and departure tasks and controlled-flight-into-terrain scenarios.

2. EXPERIMENTAL OBJECTIVES

2.1. Experimental Purpose

This experiment was designed to address two research questions regarding synthetic vision navigation displays. First, what are the effects of a synthetic vision system exocentric navigation display on situation awareness, mental workload, and pilot performance when paired with either an egocentric synthetic vision system PFD or traditional PFD? Second, could a SVS navigation display be enhanced through multi-mode 3-D formats (i.e., that allow the pilot to switch between 2-D and 3-D display perspectives)?

To answer the research questions above, six display combinations were evaluated, consisting of two primary flight displays (PFD) combined with one of three navigation displays (2 x 3). The primary flight display were either: (1) a baseline "blue sky/brown ground" PFD with standard integrated symbology, augmented with a velocity vector and pursuit command guidance cues; or (2) an exact duplicate of baseline PFD that also included egocentric synthetic terrain information. The navigation display concepts were: (1) a baseline 2-D co-planar navigation display in center map mode with Terrain Awareness and Warning System (TAWS) and Vertical Situation Display (VSD); (2) an exact duplicate of the baseline 2-D co-planar navigation display with synthetic terrain information; or (3) "Multi-Mode SVS navigation display" which was the 2-D co-planar synthetic vision navigation display with the addition of two 3-D exocentric perspectives that the pilot could choose to initiate.

2.2. Experimental Hypotheses

1. There would be no significant differences of local guidance (i.e., flight technical error) because the control guidance would be identical in both primary flight display conditions
2. Global situation awareness and pilot preference would be rated higher and mental workload lower for display conditions that had synthetic vision presented on the primary flight display
3. Global situation awareness and pilot preference would be rated higher and mental workload lower as display combinations moved from baseline combination to more synthetic vision
4. Global situation awareness and pilot preference would be rated highest and mental workload lower for the synthetic vision primary flight display and multi-mode SVS navigation display
5. Synthetic vision displays would better enable a pilot to recognize and proactively respond to potential controlled-flight-into-terrain situations than baseline displays. The highest level of situation awareness for these non-normal events will be found with the synthetic vision primary flight display and multi-mode SVS navigation display combination.

3. METHOD

3.1 Pilot Participants

Twelve commercial pilots, who fly for major commercial airlines, participated in the experiment. All participants were HUD experienced and were type-rated in the B-757. The HUD requirement was to ensure familiarity with a velocity vector and guidance symbology. All participants also had logged flight time in “glass cockpits” (e.g., A-320; MD-11) other than the B-757; therefore, all participants were familiar with a primary flight display (PFD).

3.2 Experimental Display Concepts

Six display concepts were evaluated from the full-factorial combination of two primary flight displays and three navigation displays. The primary flight displays were: (1) baseline “blue sky/ brown ground” PFD, or (2) synthetic vision PFD. The navigation displays were: (1) baseline 2-D co-planar navigation display, (2) 2-D co-planar SVS navigation display; or, (3) multi-mode SVS navigation display. Each of the display concepts are described below.

3.2.1 Primary Flight Displays. The two primary flight displays were identical to one another with the exception that synthetic vision terrain information was shown on the SVS PFD. Both PFDs had symbology typical of integrated primary flight displays including integrated altitude and speed tapes, 5 degree increment pitch scale with reference waterline, roll scale with bank indicator and a sideslip wedge and digital magnetic heading, wind speed and relative direction, heading scale conformal to the zero pitch attitude reference line (“horizon line”) with labels every ten degrees and tickmarks every 5 degrees. Airspeed, altitude, and vertical speed were presented in a nominal tape format with airspeed bugs and limit speeds present. The displays also had a flight path marker with acceleration along the flight path indicator, and reference airspeed error.

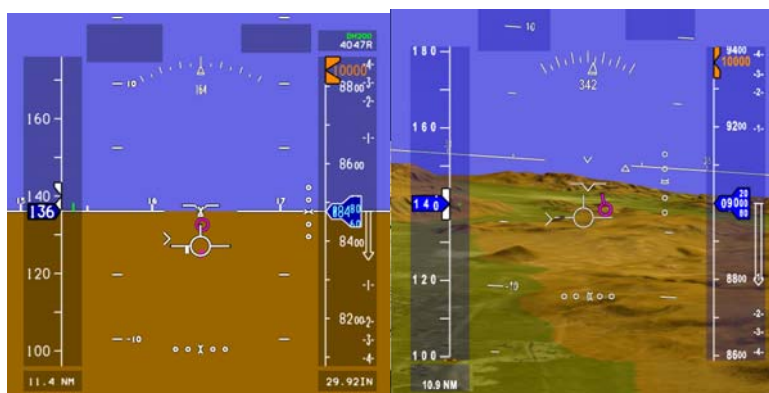


Figure 1. Head-Down Primary Flight Displays

Neither PFD display presented tunnel or “pathway-in-the-sky” information. The experiment was designed to examine egocentric and exocentric display formats and it was judged that the presence of the tunnel would bias pilots toward preferential use and reliance on the primary flight display concepts at the expense of navigation display concepts. However, flight path control and positioning information was available in the form of pathway deviation indications and

guidance cue information on the PFD. The pathway angular deviation indicators were available on the glideslope and localizer scale, which are “fly to” indications of where the aircraft is relative to a defined tunnel box of 1 dot wide and 2 dots high. The maximum dimension of the tunnel box was 600 ft. wide and 350 ft. tall with a minimum dimension of 50 ft tall.

An integrated “tadpole” guidance symbol (Merrick & Jeske, 1995, Prinzel et al., 2004) was used for both PFDs. The control laws positioning the pitch and roll guidance commands were identical for each symbol – a modified pursuit guidance control law. The guidance symbol is an integrated pitch / roll guidance cue. The pursuit command was based on path positioned 30-seconds ahead of ownship on the centerline of the tunnel with lateral track change information provided by the tail on the ball cue. The tadpole symbology is used in some military aircraft HUDs (e.g., F-16).

3.2.2 Navigation Display Concepts

Three Navigation Display (ND) concepts were evaluated: (a) baseline ND with TAWS and VSD, (b) SVS ND with TAWS and VSD, and (c) multi-mode SVS ND with TAWS and VSD. The baseline ND concept simulated present-day commercial and business aircraft equipage with TAWS and a VSD presented as a co-planar display in map-centered mode. The SVS ND was similar to the baseline ND concept with the exception of additional hybrid terrain information (see Section 3.4). The display was presented as a 2-D co-planar display in map-centered mode and had a VSD with TAWS warning and caution overlays. The multi-mode navigational concept was identical to the 2-D SVS ND concept with the exception that the pilot could initiate additional viewing modes that changed the display frame-of-reference from a 2-D “god’s-eye view” to dynamic 3-D exocentric perspective views. The specifics on these dynamic 3-D views are detailed below in Section 3.3.

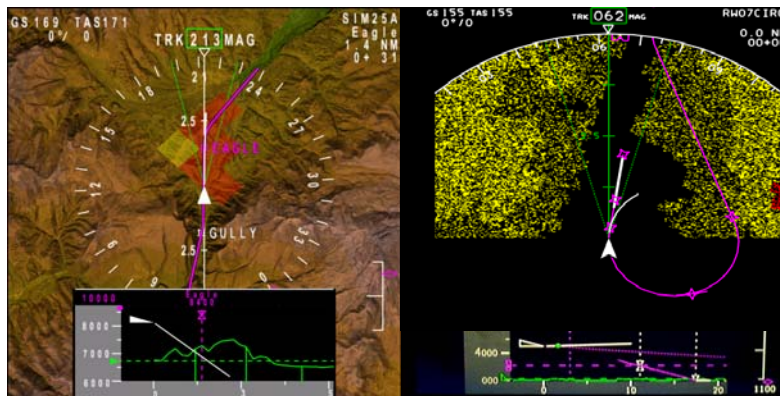


Figure 2. Baseline and SVS Navigation Display Concepts

3.3 Dynamic 3-D Modes

Under the multi-mode SVS navigation display condition, there were two 3-D exocentric navigation display modes that the pilot could initiate. The first mode was termed “animate” and is analogous to a now-common cinematic special effect in many modern martial arts movies as a way to give the viewer a sense of being part of the action or being “immersed”. The “animate” mode of the 3-D exocentric navigation display concept behaved as shown in the image sequence in Figure 3. When the pilot initiated this mode the navigation display went from the (a) SVS 2-D co-planar view to a (b) 20 degree right offset view at a distance of 5000 feet that zoomed out to (c) 10000 feet then (d) panned to the left to (e) 20 degrees azimuth on the other side of the view point at same camera tether length and then zoomed in to (f) 5000 feet and then rotated up to a (g) 90 degree view look-down to ease the transition from the 3-D to the (h) 2-D perspective. At each viewpoint, the view would hold from 1 to 3 seconds. The pan and zoom functions were smooth.

A second pilot-initiated mode was called “perspective” and is illustrated in Figure 4. When the pilot initiated this mode, the view would change from the 2-D SVS co-planar view to a (a) 20 degree right offset view at 10000 feet (hold for 5 seconds) and the switch to a (b) 20 degree left offset view at 10000 feet (hold for 5 seconds) and then back again to 2-D SVS co-planar view.

The objective of both modes was to provide pilots with improved path and situation awareness using the exocentric perspective display. These views would “time out” to preclude the possibility that a pilot might leave the navigation display in that mode and attempt to use it for primary navigation.

3.4 Terrain Texture Database

The synthetic terrain database for all SVS concepts was 95 nmi by 95 nmi in area, centered at the Eagle-Vail Regional County Airport (EGE) airport in Colorado. The digital elevation model used 1-arcsecond (30 meter) resolution data with a Universal Transverse Mercator (UTM) WGS84 projection. The accuracy of the source data was within 12 meters (90% of data) horizontal and 7 meters (90% of data) vertical. The SVS terrain was rendered in a hybrid textured format. This hybrid texture was created from ortho-rectified aerial photographs of the EGE area merged with elevation-based color-coded digital elevation terrain model. The imagery for the hybrid texture was nested such that high-resolution photographs (1 meter per pixel) were used in close proximity to the EGE airfield and the majority of the database used 4 meters per pixel resolution imagery. The elevation model color-coding used a green color for the field elevation of EGE airport tending toward shades of brown for higher elevations using 12 elevation color bands that were 250 meters in elevation. The 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.

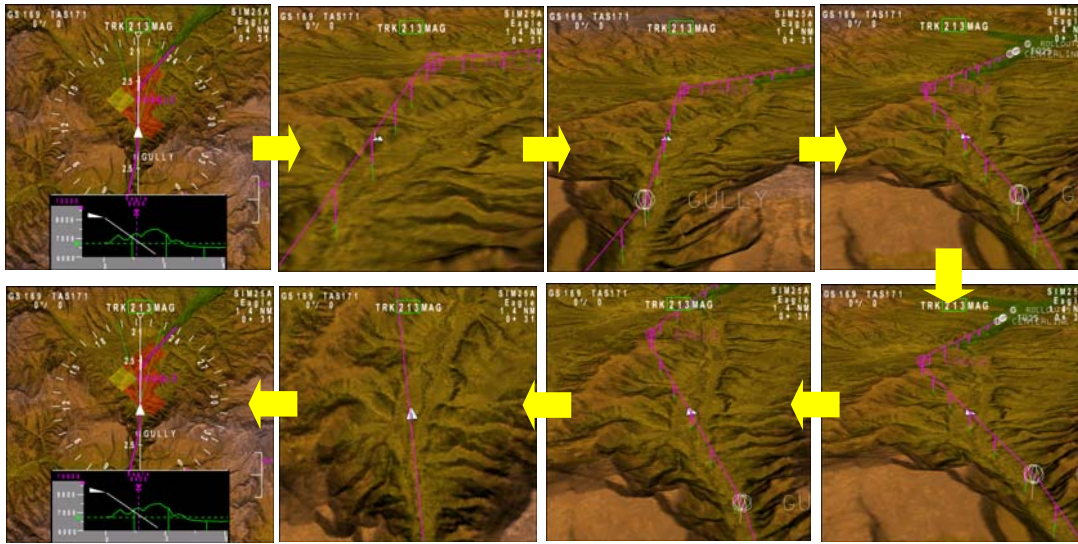


Figure 3. Static Screenshots of Dynamic “Animate” Mode Sequence

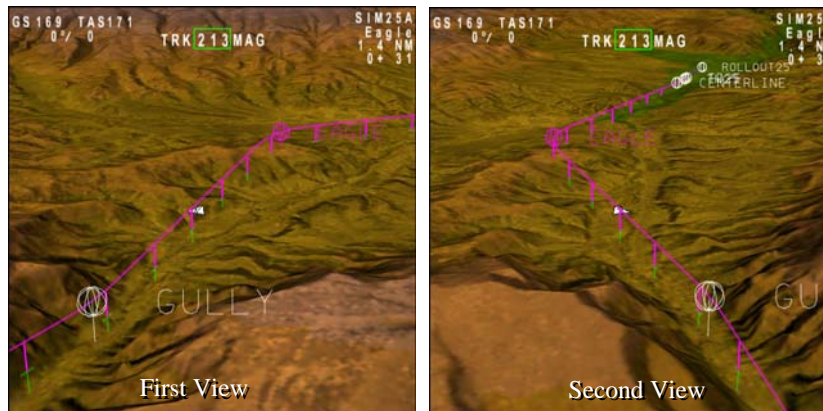


Figure 4. Static Screenshots of “Perspective” Mode Sequence

3.5 Experimental Tasks

Each pilot flew thirteen approach and six departure tasks for a total of nineteen runs. The experimental runs combined one of eight initial conditions (IC) with one of five flight paths (see Table 1). IC #1-6 (1 replicate) was used for the approach tasks and IC#8 was used for the departure task. The approach tasks used either SIM 25A, B, or C and the departure task used either SIM 07A or SIM07B. The thirteen approach tasks were comprised of two replicates of IC# 1-

6. IC #7 was used for the approach CFIT scenario. The six departure tasks were comprised of IC #8 combined with one of two departure flight paths. IC #8 with SIM 07B was used for the departure CFIT scenario. Table 2 shows the IC cases and flight paths with Lat, Long, MSL alt., and true heading information. Table 2 presents the details of the flight path flown for the approach and departure scenarios. Descriptions of the experimental scenarios and CFIT scenarios (Sections 3.5.1 and 3.5.2) are detailed below.

3.5.1. Experimental Approach Scenarios

Each scenario began with specific ATC instructions tailored to the scenario. Pilots were instructed that their primary responsibility was safety of the aircraft and avoidance of terrain. Pilots had the option not to accept and/or comply with any ATC clearance if it presented a hazardous situation.

The pilot was instructed by simulated Air Traffic Control (ATC) instructions to fly various flight paths from their pre-set IC as shown in Figure 5 until reaching a final waypoint named “EAGLE” (Figure 5). All approach scenarios took the aircraft through a “notch” between two mountains at waypoint “GULLY”. The rare event CFIT scenario for the approach began at IC #7 with an ATC instruction to fly a “direct to” GULLY which took the aircraft over high terrain.

Table 1. Scenario Initial Conditions Information.

Initial Condition	Latitude	Longitude	MSL Altitude (ft)	True Heading (deg)	Path
1 Approach	N39.8260	W106.4894	12500	236	Sim 25C
2 Approach	N39.9120	W106.4812	13500	198	Sim 25A
3 Approach	N39.8485	W106.4462	12500	236	Sim 25C
4 Approach	N39.8320	W106.5144	12500	198	Sim 25B
5 Approach	N39.7078	W106.4895	12500	285	Sim 25B
6 Approach	N39.9255	W106.5440	13500	018	Sim 25A
7 Approach (CFIT)	N39.99092	W106.65508	13500	195	Sim 25A
8 Departure	N39.6410	W106.9318	6656	082	Sim 07A/B

Table 2. Textual Description of Experimental Scenarios

SIM 25-A/C (Runway Elevation 6535')	<ol style="list-style-type: none"> 1. <u>Prior to Run</u>: altitude $\geq 15,000'$ 2. <u>After RLG Outbound on 184 Radial to PINEY</u>: Begin descent to 12,500' (3253' AGL) at PINEY. 3. <u>At PINEY</u>: turn right to 223° Mag track, descend to 8400' (1575' AGL) by GULLY. 4. <u>At GULLY</u>: turn left to 212° Mag track, level at 8400' (924' AGL) by EAGLE 5. <u>At Eagle</u>: turn right to 251° Mag track , begin 3 deg descent to 6735' (200' AFL) at intercept 6. <u>At glideslope / extended-centerline intercept</u>: (6,735', 200' AFL) turn left to 249° Mag track
SIM 25-B (Runway Elevation 6535')	<ol style="list-style-type: none"> 1. <u>Prior to Run</u>: altitude $\geq 15,000'$ 2. <u>After RLG Outbound on 184 Radial to PINEY</u>: Begin descent to 12,500' (3253' AGL) at PINEY. 3. <u>At PINEY</u>: continue outbound on 184° Radial. Continue descent to 12,000' at ALPHA. 4. <u>At ALPHA</u>: turn right to 272° track, descend to 9700' by BRAVO. 5. <u>At BRAVO</u>: turn left to 223° track, descend to 8400' by GULLY. 6. <u>At GULLY</u>: turn left to 212° track, level at 8400' (924' AGL) by EAGLE 7. <u>At Eagle</u>: turn right to 251° track , begin 3 deg descent to 6735' (200' AFL) at intercept 8. <u>At glideslope / extended-centerline intercept</u>: (6,735', 200' AFL) turn left to 249° track
Departure SIM 07A/B	<ol style="list-style-type: none"> 1. <u>Crossing end of Runway</u> : 6756' MSL. Turn left to 044° Mag track, begin climb to 7556' at D68_SXW 2. <u>At D68_SXW</u>: Turn right to 059° Mag track, continue climb to 12,460' at I059_SXW. 3. <u>At I059_SXW</u>: Turn left to 352° Mag track, continue climb to 15,000' by Kremmling. 4. <u>At Kremmling</u> : Continue on 352° Mag track, maintain 15,000' to Arthur.

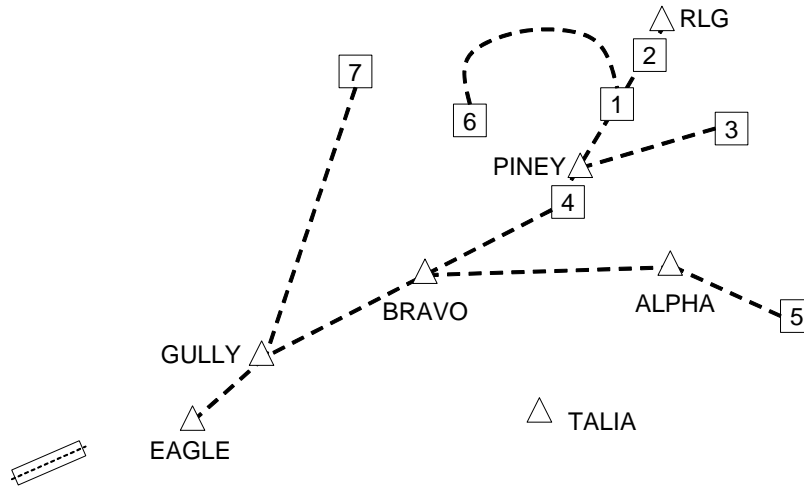


Figure 5. Experimental Nominal and CFIT Approach Scenarios

3.5.2. Experimental Departure Scenarios

The departure scenarios simulated reduced 757 engine climb performance that required that the aircraft fly back through the notch at GULLY in order to avoid high terrain in all quadrants. The departure task was to follow a heading of 050 degrees until the aircraft was at 6.8 nautical miles distance measuring equipment (DME) from the Snow Very high frequency Omni-directional Range (VOR). At the 6.8 DME point, the pilot was then to follow the 059 radial from the Snow (SXW) VOR. For the final data run of the experiment, the rare event scenario, the flight guidance was altered on the departure path (dotted path in Figure 6). Both the flight path and guidance cues directed the airplane into a mountain peak.

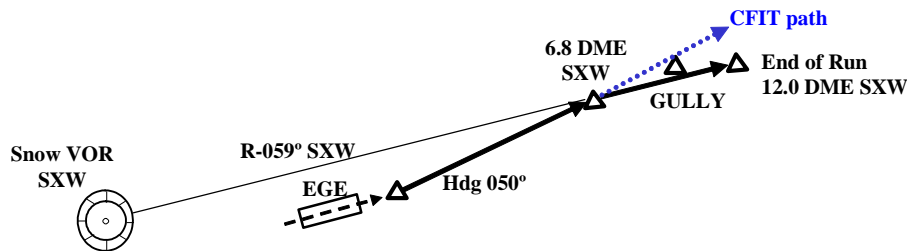


Figure 6. Experimental Nominal and CFIT Departure Scenarios

3.6 Simulation Facility

The experiment was conducted in the Visual Imaging Simulator for Transport Aircraft Systems (VISTAS) III simulator at NASA Langley Research Center (Figure 7). The single pilot fixed based simulator consists of a 144° by 30° Out-The-Window (OTW) scene, a large field research display (SVS-RD) and pilot input controls. The OTW scene was presented with unlimited visibility during simulation training and was reduced to ¾ nm for the experimental runs. The SVS-RD consisted of 18.1-inch high brightness dual-glass XGA LCD monitors, closely abutted to give a seamless impression. The pilot controls in the VISTAS III workstation are a left side arm controller, center-pedestal throttle controls, rudder pedals, toe brakes, and a voice recognition system (VRS). The VRS is a speaker-independent voice recognition system that provided a robust, rapidly re-configurable pilot-vehicle interface. It was also used to provide automated alerts, warnings, and simulated ATC commands. The aircraft model was a B-757, and the selected airspeed was 140 knots. All scenarios were flown with moderate turbulence. Auto-throttles were used and the aircraft landing configuration was set.

3.7 Experimental Design

The experimental design was a 2 (experimental task) X 6 (display conditions) X 2 (nominal, rare event) X 12 (pilots) mixed-subjects experimental design. All pilots flew each approach and departure nominal scenario with all six display

conditions. There was one replicate of each of the six nominal approach scenarios (2 runs each of IC#1-6). For the CFIT scenarios, each pilot experienced one approach and one departure CFIT scenario. Therefore, the independent variable was a between-subjects factor and was counterbalanced across pilots to yield two data points for each of the six display combinations for both CFIT scenarios (providing 12 total data points for each CFIT scenario). Flight technical error and other performance metrics were recorded. After each run, pilots completed a run questionnaire (7-point Likert Scale) and the Revised Workload Estimation Scale (Ames & George, 1993). Upon completion of all experimental runs, pilots filled out the SWORD and SA-SWORD (Vidulich & Hughes, 1991) for evaluation of (a) PFD + ND display combinations and (b) ND concepts only. A final debriefing questionnaire was also administered. Data was analyzed using parametric (ANOVA) statistics and Student Newman-Keuls (SNK) post-hoc tests. Alpha was set to .05.



Figure 7. Visual Imaging Simulator for Transport Aircraft Systems (VISTAS) III

4. RESULTS

4.1 Flight Technical Error

There were no significant differences found for flight technical error for the conditions of display, path, or interactions ($p > .05$). The total root-mean-squared (rms) path error was 97.32 ft. lateral and 63.43 ft. vertical. These path performance results are not surprising. Each display concept utilized the same pursuit guidance control laws and symbology (i.e., the flight path marker, integrated single cue guidance symbol and path deviation indicators). These results are also supported by past research (Kramer et al., 2004, Prinzel et al., 2004). It should be noted that the FTE results do not fully include the influence of off-path starting conditions because the FTE results were normalized by using the point of path intercept to begin the FTE “scoring.”

4.2 Mental Workload

An ANOVA revealed a significant main effect for Revised Workload Estimation Scale ratings for mental workload, $F(5,55) = 2.695$. The SNK showed that pilots rated the SVS PFD + SVS ND to be significantly lower in mental workload than the Baseline PFD + Baseline ND. No other displays were significantly different from each other. The SWORD analysis also found a significant effect for mental workload, $F(5,55) = 8.775$. There were two unique SWORD subsets found: (a) SVS PFD + SVS ND, SVS PFD + Baseline ND, SVS PFD + SVS Multi-Mode ND and (b) Baseline PFD + SVS ND, Baseline PFD + SVS Multi-Mode ND, Baseline PFD + Baseline ND. Displays were not significantly different from each in their unique subsets (i.e., a or b).

The results evince that the presence of a SVS PFD regardless of ND concept reduced workload compared to any display combination of Baseline PFD and ND concepts. This was supported by the analysis of SWORD on ND concepts only in which no significant effect was found. Pilots rated the three ND concepts as demanding equal amounts of mental workload.

4.3 Situation Awareness

After each run, pilots rated their situation awareness of aircraft position with respect to terrain. There was a significant main effect for display conditions for SA, $F(5,55) = 17.801$. Pilots rated their SA significantly higher with the SVS PFD + SVS Multi-Mode ND compared to the other five display combinations. The Baseline PFD + Baseline ND was rated significantly lower in SA than all other display conditions.

Pilots estimated that they obtained 60% of terrain information from the SVS PFD compared to the SVS Multi-Mode ND display (40%). However, when pilots only had synthetic vision on the PFD, the estimate went up to 85%. The presence of synthetic vision on the ND (2-D co-planar only) provided little enhancement of terrain awareness and pilots reported

an increase of only 10% (75% SVS PFD, 25% SVS ND). The SVS Multi-Mode ND increased that terrain awareness estimate by 15% (60% SVS PFD, 40% SVS ND). When pilots did not have synthetic vision on the PFD, pilots gave 100% ratings to the ND display regardless of ND display concept. The result is understandable as the Baseline PFD provides no terrain awareness information when synthetic vision is absent.

The SA-SWORD analysis revealed a significant effect for PFD+ND display conditions, $F(5,55) = 60.852$. Like the post-run Q results, pilots gave significantly higher SA-SWORD ratings for the SVS PFD + SVS Multi-Mode ND conditions compared to the other display conditions. Pilots rated the Baseline PFD + Baseline ND to have provided the lowest SA. The rank order for both the SA post-run Q and SA-SWORD are: (1) SVS PFD + SVS Multi-Mode (highest), (2) SVS PFD + SVS ND, (3) SVS PFD + Baseline ND, (4), Baseline PFD + SVS Multi-Mode ND, (5) Baseline PFD + SVS ND, and (6) Baseline PFD + Baseline ND (lowest). There were four unique subsets with no significant differences between (a) Baseline PFD + Baseline ND and Baseline PFD + SVS ND and (b) Baseline PFD + SVS Multi-Mode and SVS PFD + Baseline ND. Otherwise, the displays were significantly different from each in the relative rank order.

The results suggest that the SVS PFD is an essential display concept for SA but also that the SVS Multi-Mode ND concept provided a similar level of SA enhancement when paired with a Baseline PFD compared to a SVS PFD paired with a Baseline ND. If they are combined together, the highest level of SA was reported for SVS PFD + SVS Multi-Mode ND.

The SA-SWORD analysis for ND only also showed that pilots considered the SVS Multi-Mode ND to have provided the highest SA compared to either the Baseline ND or the SVS ND (which were not significantly different from each other), $F(2,22) = 47.175$. During final debriefing, the majority of pilots felt that having SVS on a 2-D god-eye ND did not provide much improvement for SA compared to just a baseline ND. Instead, SVS provided much higher SA benefits when presented on an egocentric PFD. However, when the SVS ND also has the multi-mode features, the SVS Multi-Mode ND was rated to have significant utility and potential for SA enhancement particularly during non-normal operations.

4.4. Pilot Preference

Pilots were asked to complete a paired comparison scale that allowed them to make judgments on their preferences for which display concepts they would most want to have onboard their aircraft. Pilot preference is subjective and has other factors considered than just workload or situation awareness. However, pilots provided a similar rating for pilot preference and most preferred the SVS PFD + SVS Multi-Mode ND and least preferred the Baseline PFD + Baseline ND, $F(5,55) = 68.611$. The rank order was identical to that found with the SA-SWORD paired comparison analysis. When asked their preference for ND only, pilots preferred the SVS Multi-Mode ND, then the SVS ND, and finally the Baseline ND, $F(2,22) = 141.063$. Overall, the pilot preference paired comparison analysis suggest that pilot most prefer synthetic vision on the PFD, but that a SVS Multi-Mode ND is highly preferred by pilots. In general, pilots most preferred the SVS PFD + SVS Multi-Mode combination.

4.5. Controlled-Flight-Into-Terrain

All pilots avoided terrain during both the approach and departure CFIT scenarios. However, there were marked differences in how pilots responded to the non-normal event. Two pilots experienced the approach CFIT scenario flying the Baseline PFD + Baseline ND concept. Two pilots flew the CFIT scenario flying the Baseline PFD + Baseline ND concept. While neither condition resulted in a CFIT, one pilot missed the terrain by less than 100 ft during the approach. During the departure, both pilots executed an abrupt pitch up/climb to narrowly avoid the terrain (<300 ft).

When synthetic vision was presented on the PFD, however, pilots were much more proactive and were able to execute both lateral and vertical maneuvers often with enough time to avoid TAWS and/or VSD alerts.

Because the PFD has a limited field-of-view and it can sometimes be difficult to make depth judgments as to how far a particular piece of terrain is in the egocentric view, the addition of the SVS Multi-Mode ND significantly enhance the timing and decision-making ability of pilots to avoid the CFIT. In fact, pilots initiated the evasive maneuvers so quickly that the aircraft avoided the terrain by significant measure. In three cases, the pilots immediately upon beginning the departure scenario identified the CFIT situation because the 3-D exocentric view showed that the flight path was intercepting the terrain at GULLY. Without the SVS Multi-Mode ND, pilots were still able to successfully avoid the terrain, particularly with the SVS PFD, but they did so by initiating evasive maneuvers only once they recognized the situation; at an approximate distance of 3 nautical miles from GULLY. While they had enough time to avoid the terrain and executed a vertical (when using a Baseline PFD) or the better lateral maneuver (when using an SVS PFD), there was

a substantial difference in time to recognize and respond when the SVS Multi-Mode ND was also available. It increased the time to respond an approximate average of 2.5 minutes - significantly enhancing the safety margin.

4.6 Other Results

Several other run questions were asked that evaluated the effect of winds and turbulence, display clutter, and subjective estimates of pilot performance with no significant practical effects. Pilots did provide substantive feedback on how to enhance the SVS Multi-Mode ND. Most pilots felt that the “animate” mode took too long to go through the display sequence, and that several viewing points could be eliminated to provide the SA needed. Pilots were concerned that when flying in instrument conditions the dynamic nature of the “animate” mode coupled with the time required to monitor the display sequence may induce spatial disorientation. When optimized, however, all pilots felt that the issue was minimized. Few pilots felt that the “perspective” mode needed to be changed although suggestions were given on what other information could be presented to take advantages of the uniqueness of the ND concept. These are being considered for future versions of the SVS Multi-Mode ND.

When asked to state their preference for either “animate” or “perspective”, most pilots reported that the “perspective” mode was best. It provided the SA regarding flight path and terrain awareness they needed with minimum cognitive and attentional investment. However, pilots felt that the animate mode does have its uses particularly during low workload phases of flight in which the display mode could be used to brief and rehearse an approach, missed approach, etc. All pilots thought that a most useful feature (rating of 7.0/7.0 or “must have”) would be the use of the modes as a tool for validating flight paths (e.g., before FMS execution of a modified path), rehearsal of complex procedures (e.g., T-procedures or engine-out, complex missed approach, depressurization routes in high terrain), and graphic flight crew briefing of unfamiliar airport environments. Many other examples were provided owing to the significant potential of the SVS Multi-Mode ND to enhance local guidance knowledge and global situation awareness.

5. CONCLUSIONS

Technology has advanced to allow for the emergence of synthetic vision systems that will fundamentally change how aircraft are operated in instrument conditions. By creating a virtual visual meteorological condition, synthetic vision holds the promise to mitigate the precursor to many accidents and incidents and substantially improve the safety and operational efficiency of aviation. This paper described an experiment primarily designed to:

- Evaluate the effects of a SVS exocentric ND when paired with either an egocentric SVS PFD or traditional PFD and
- Assess whether a SVS ND can be enhanced through 3-D multi-mode formats that allowed the pilot to switch between 2-D and 3-D exocentric perspective views.

5.1. Situation Awareness Benefits

The results showed that synthetic vision on the PFD was primary for pilot use in terrain avoidance and situation awareness. On the other hand, synthetic vision terrain on the 2-D co-planar NAV was not found to provide much benefit. Pilots noted that synthetic terrain adds to the clutter on the ND without much enhancement of terrain awareness.

The situation awareness ratings for the SVS PFD were largely due to the egocentric view which gave the pilots an immersed sense of the terrain around them. However, because it is an egocentric view, the display does have “keyhole” limitations which may be overcome when supplemented by an exocentric view. The 2-D gods-eye exocentric SVS ND, however, was not found to add much additional situation awareness compared to the baseline NAV. But, when the 2-D SVS co-planar display was enhanced with the multi-mode exocentric features, pilots significantly rated their situation awareness higher.

The second empirical question concerned whether human factors issues involved with different exocentric views could be minimized by making them all available for use by the pilot. 2-D co-planar NAV displays have significant advantages but do not allow the capability of synthetic vision technology to reach full potential. Our hypothesis was that display format human factors issues may be overcome through pilot-initiated “situation awareness” modes that provide the 3-D exocentric perspective that enable better global situation awareness. However, because such perspective displays may not be well suited for making precise judgments and decisions, 3-D exocentric displays may instead be best used as an “SA tool” to supplement the information being supplied by a SVS PFD and 2-D SVS co-planar ND. Therefore, when 3-D exocentric displays are used for situation awareness use coupled with the egocentric PFD and more

traditional exocentric 2-D SVS ND display format, the benefits afforded each display format are realized with few of the penalties witnessed if the displays were evaluated independently. The experimental data confirmed our hypothesis that a 3-D exocentric multi-mode navigation display effectively and significantly enhanced pilot situation awareness.

5.2 Controlled-Flight-Into-Terrain

The situation awareness ratings were supported by the controlled-flight-into-terrain behavioral data. Pilots experienced several incidents while flying with the baseline displays during both the departure and approach CFIT scenarios. While pilots did not experience any CFIT incidents when synthetic vision was available on either the PFD or NAV, there was a marked difference in how pilots managed the non-normal event. Pilots were effectively able to manage the CFIT situation when synthetic vision was presented on the PFD. However, when pilots also had the SVS Multi-Mode ND display available to them, they were able to execute proactive evasive maneuvers often well before the terrain presented a danger to the aircraft. This contrasted with pilot response to the CFIT with the baseline PFD paired with either a SVS 2-D co-planar NAV or baseline NAV. In those cases, pilots were ill-equipped to recognize the hazardous situation and instead were reactive to TAWS alerts significantly limiting reaction time and options to avoid terrain. In contrast, when the SVS Multi-Mode ND was available (with or without SVS PFD), pilots used the 3-D exocentric information to realize that the flight trajectory would place them perilously close to terrain and make proactive decisions that avoided the need for a TAWS or VSD alert. They never got into a situation that warranted the need for evasive action. In fact, those pilots that had both a SVS PFD + SVS Multi-Mode ND were often able to question the ATC clearance initially and make necessary changes to flight path to avoid high terrain by a wide margin.

Overall, synthetic vision depicted on the PFD is essential for situation awareness. However, pilot awareness and capability for avoiding hazardous conditions was significantly enhanced with the addition of the 3-D exocentric modes because it allowed for a greater field-of-regard to confirm the presence of hazards. Together, the combination of synthetic vision display concepts allowed pilots to make the best and quickest decisions regarding safety of the aircraft.

5.3. Future Directions

The experiment produced a substantial amount of data that will be used to further enhance the functionality of the SVS Multi-Mode ND display. Future research in this area will also focus on how best to design the “rehearsal” capability of the display concept to allow pilots to utilize the display to graphically rehearse nominal and off-nominal procedures for better global situation awareness.

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