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Synthetic Vision Applied to General Aviation: An Evaluation of Pilot Performance and Preferences When Using Head-up, Head-down, and Head-mounted Synthetic Vision Displays for SA CAT I Approaches in Flat Terrain and Missed Approaches in Challenging Terrain

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16. Abstract

Twenty instrument-rated General Aviation (GA) pilots completed SA CAT I approaches to KOKC and three localizer approaches to KASE followed by missed approaches across two phases of research in a high-performance single-engine GA flight simulator. The approaches were conducted in two levels of runway visual range (RVR) and with two decision heights (DH) using three display platforms (Phase 1, head-up and head-down; Phase 2, head-up and head-mounted) presenting Synthetic Vision (SV). It was determined that a lower DH led to significantly more completed approaches while a higher DH was more likely to cause pilots to execute missed approaches. RVR was not a significant factor for those values examined. SV was determined to be most beneficial for missed approaches in challenging (mountainous) terrain, but not as much of a factor on the initial approach. Evaluations of cross-track and glide-slope RMS error for the approaches to KOKC did not show a reliable differentiation between display conditions, nor was there any consistent operationally significant difference between touchdown points. Pilots uniformly believed that they could successfully and comfortably complete approaches in lower visibilities if SV equipped (either display platform) as compared with a Primary Flight Display (PFD) without SV or with round-dial instrumentation.

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List of Acronyms

Acronym	Term
AFS	Federal Aviation Administration Flight Standards Service
AGL	Above Ground Level
CAMI	FAA Civil Aeromedical Institute
C/L	Center Line
CAT I	Category I
DA	Decision Altitude
DH	Decision Height
FAA	Federal Aviation Administration
FPV	Flight Path Vector
GPS	Global Positioning System
HDD	Head Down Display
HIRL	High Intensity Runway Lights
HUD	Head Up Display
ICAO	International Civil Aviation Organization
ILS	Instrument Landing System
MSL	Mean Sea Level
OTW	Out the Window
RVR	Runway Visual Range
SA CAT I	Special Authorization Category I
SV	Synthetic Vision
SVGS	Synthetic Vision Guidance System
SVS	Synthetic Vision System
TDZ	Touchdown Zone

Background

Representations of terrain and cultural features in a forward-looking pictorial fashion (Synthetic Vision; SV) are now found on numerous avionics displays. While many of the desired qualities and features, as well as pilot performance using this type of imagery on differing display platforms (both head-up and head-down), have been researched, reported, and documented (e.g., Domino et al., 2015; Beringer & Ball, 2009; Beringer, 2016; Kramer et al., 2013; RTCA, 2015), it has not been resolved fully as to what extent operational credit for reduced-visibility minimums can be awarded when the aircraft is equipped with such a display.

One study that looked at similar display platforms and formats examined differences in pilot visual behaviors seen between using head-up and head-down versions of the SV display, with the intent of adding data to the operational-credit discussion. While the results suggested that there was a benefit to the use of a HUD regarding head-down time being reduced, the simulation platform was modeled after the B 757-200 and used participants who had ATP ratings and experience with SVS and EVS (enhanced vision systems), most likely from Part 121 or 135 operations (Ellis, Kramer, Shelton, Arthur, & Prinzel, 2011). This did not directly address the General Aviation (GA) environment (Part 91) as it relates to typical aircraft performance, pilot experience level, and target airport infrastructure. Another study (Beringer, 2016), the first phase of this research effort, examined GA pilot performance with and opinions of synthetic-vision-depicting displays in both head-down (HDD, electronic PFD) and HUD formats. Those result are reported herein as a means of grouping both phases of the GA examinations together to facilitate referencing and gather the related results into a single report.

An Advisory Circular on this topic, AC 20-185 (FAA, 2015), "Airworthiness Approval of Synthetic Vision Guidance System," addresses guidance for obtaining airworthiness approval (and only for applicants for eligible SVGS for Special Authorization Category I – SA CAT I - ILS instrument approach procedures), but clearly states in 1.1.3, "At this time, the FAA is not authorizing the use of SVGS as the means to descend below 200 feet HAT on LPV or GLS instrument approach minimums" (p. 1). In addition, paragraph 1.2.2 states, "This AC does not address operational aspects of SVGS or any changes in aircraft operational capability that may result from installation of these systems" (p. 2). The data collected here were intended to assist in determining if approach credit for lower minima were possible, and to explore candidate values, provided by the sponsor, for both Decision Height (DH) and Runway Visual Range (RVR). It should be noted that a follow-up AC was in the works at the time of these studies that might approve operations to lower minima depending upon the specifics of equipment installed in the aircraft.

Inasmuch as the number of conditions and display platforms were slightly more than could be comfortably accommodated within a single study, the experimentation was separated into two study phases. The first, initially reported in Beringer (2016) as noted previously, is repeated here and was intended to compare pilot performance when using the head-up display (baseline) versus that attainable using a head-down version of the synthetic-vision primary flight display. Phase 2 of the research was designed to replicate Phase 1 but to use a head-mounted display (HMD) as the comparison display platform to the HUD.

Method – Phase 1

Experimental Design

A within-subject design was chosen to attempt to minimize variation attributable to differences between participants as well as to reduce the overall number of participants that would be required by introducing between-groups variables. The variables examined included:

Independent Variables. The manipulated variables included:

- Display location (2); head-up (HUD), head-down (HDD)
- Synthetic Vision Imagery (2); present, absent
- Runway Visual Range (RVR) (2); 1200, 1400 ft.
- Decision Height (DH) by approach type
    - SA CAT I approach, KOKC (2); (100 ft., 150 ft.)
    - Localizer approach to KASE (1); (200 ft.)

Dependent Variables. Performance measures included:

- Flight-performance technical error
    - Glideslope (GS) error (KOKC approach)
    - Localizer (LOC) error (both approach types)
    - Touchdown point
    - Frequency of missed approach on SA CAT I
- Questionnaire data
    - Perceived workload (posttest interviews)
    - Opinion data on acceptable visibility levels (Appendix C)

Baseline conditions. Two types of baseline conditions were included for comparison to the experimental conditions. These included:

- Using the head-down Electronic Primary Flight Display (EPFD) without terrain imagery (2 trials)
- Using conventional round-dial instrumentation (1 trial)

Equipment

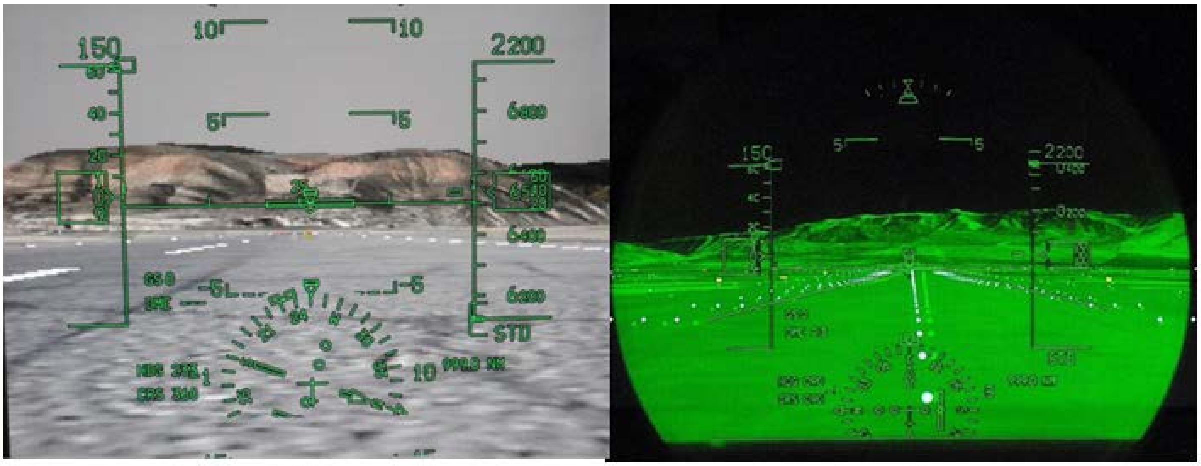
A research-configured flight simulator (Advanced General Aviation Research Simulator; AGARS) representing a Piper Malibu/Meridian (Figure 1) with head-up and head-down electronic primary flight displays (EPFDs) and an electronic moving map was used as the research platform. The head-down EPFD (Figure 2A) could present the equivalent of an Electronic Attitude Direction Indicator (EADI) using HUD symbology with or without a full-color Synthetic Vision background depicting terrain and cultural features such as airports, runways, and buildings. The HUD (Figure 2B) presented the same imagery, excepting that the underlay of terrain and cultural features was shown in monochrome using varying levels of green.

Participants

Eight local male instrument-rated GA pilots participated in Phase 1. Median age was 47 years (range, 25 to 61), median years flying was 30 (range, 6 to 40). Median hours total flight time was 675 (range, 292 to 1945). Half had limited experience with electronic flight displays and the other half had used Garmin, Aspen, or Avidyne systems.

Figure 1. The Advanced General Aviation Research Simulator (AGARS) with HD, EPFD, HUD, and electronic map

display.



A B

Figure 2. The head-down primary flight display (HDPFD) (A) and the head-up display (HUD) (B).

Figure 3. The round-dial baseline instrumentation panels.

Tasks

Task 1, SA CAT I Approach. This task was considered of primary importance as it had an immediate relevance to operational credit, with the potential for using a head-down primary flight display employing synthetic-vision imagery in lieu of an installed HUD. Pilots were required to perform the SA CAT I approach to Oklahoma City (KOKC, Will Rogers World Airport), runway 35R (see Appendix A), for each of the cells in the design. A repeated baseline condition was used for the first and last trials; 1400 RVR, DH 100, HDD without terrain imagery. An additional reference trial was inserted in the approximate middle of the order, depending upon the counterbalancing, that used the same visibility conditions as the other baselines but required the use of round-dial glideslope/localizer instrumentation. The plate for this approach is shown in Figure A1 (see Appendix A).

Task 2, Cross-country flight with approach and missed approach at destination. This task was introduced to assess how the presence of SV in the HUD might benefit operations in vertically challenging terrain, specifically in aiding the piloting in avoiding terrain, both during an approach to and a departure (missed approach) from an airfield situated in such terrain. Pilots flew the localizer approach to Aspen, CO (KASE) three times; once with each display configuration (HDD w/o terrain but with runway outline, HDD and HUD w/terrain). Two counter-balanced orders were used across participants. The ceiling was between 300 and 250 feet AGL, with the RVR greater than 3 miles upon breakout and DH was set at 200 feet. The published approach is a step-down approach and has only localizers, one for inbound and one for outbound on the missed approach, and no glideslope. The approach was flown with a constant descent angle from top of descent by using the (instantaneous) flight-path marker symbol. A plot of the reference path plotted over the terrain is shown in Figure A2 (Appendix A).

Procedure

Participants began the session with a pilot-experience questionnaire (see Appendix B) and then progressed to a familiarization flight in the simulator. They flew the simulator until they felt comfortable with their ability to maneuver and land and their questions about displays or tasks had been answered by the experimenter. Participants were then briefed on the first task and procedures and flew a warm-up approach to KOKC 35R. This was repeated if any difficulties were experienced with the approach or the procedure.

Task 1. Data flights consisted, in order, of one baseline trial (HD PFD), four experimental trials, one round-dial reference trial, four experimental trials, and one baseline trial (HD PFD). All approaches to KOKC were flown from a simulated ‘air start;’ in this case, from a modeled ‘floating’ runway in line with the LOC and just below the GS so that a slight climb to 3000 feet MSL and level off put the aircraft on the proper heading and altitude to intercept the GS at an indicated distance from touchdown of 7 miles. The start point was at 2700 feet MSL and 10 miles south of KOKC (per DME indication). The pilot was required to set the course line on the horizontal situation indicator (HSI) to match the LOC course line. The safety pilot/experimenter operated the flaps, per participant’s requests, to simplify the procedure. The pilot was required to call runway in sight at DH or execute the missed approach if the runway was not in sight. Approaches continued to landing if the runway was in sight at DH. Missed approaches were continued until a stable configuration and climb were achieved. The primary focus of Task 1 was pilot behavior during the approach. Each approach was approximately 4 mins and 30 secs in length from simulator release to end of rollout.

Task 2. KASE segments (3) were all flown as complete missions from KEGE (Eagle County), which is to the north of Aspen, to Aspen (KASE). Participants took off from KEGE, climbed to 13,000 feet while making a procedural turn at 500 feet AGL to the south to intercept the localizer for KASE, initiated descent at the top-of-descent radial off of the Red Table VOR, and made a continuous descent to KASE using the flight-path marker to keep the projected contact point near the TDZ. The actual break-out altitude was between 250 and 300 feet AGL. Upon reaching the DH at 200 feet, the pilot was instructed to execute the missed approach. This required an immediate climbing right turn to intercept the outbound LOC, heading 303 degrees with course needle set to reciprocal, and a climb to 13,500 feet. The missed approach was continued until the aircraft was established on the outbound course or until the flight track had diverged sufficiently to appear unrecoverable. The primary focus of Task 2 was pilot behavior during the missed approach only.

It should be noted that a conformal HUD image was used as would be expected. This was appropriate for approach as the terrain was always visible under the nose in a descent-pitch attitude. However, the terrain image dropped out of the bottom of the PFD on the missed approach at 12 degrees pitch up. This, again, suggests a need to increase pitch scale, as determined in previous experiments and done on some HUDs, for climbs and missed approaches so that the flight-path marker and top of terrain will remain within the display field of view.

Posttest interview/questionnaire. Immediately following the final data collection flight, the pilot was debriefed and participated in an interview and questionnaire session (see Appendix C). The post-flight questionnaire included the following questions:

- What minima would be acceptable to you with each display configuration/equipment?
- What features of the SVS did you find useful?
- What features of the SVS did you find distracting?
- What type of training in the use of this equipment would you prefer? (Selected from list)

The questionnaire was followed by other open-ended questions and a discussion and explanation of the goals of the study.

Results and Discussion – Phase 1

Task 1, SA CAT I flight technical error

RMS error for LOC and GS. The analysis of root-mean-square (RMS) error on approaches to KOKC showed consistency across display types, with no significant differences seen. This was not surprising given that the error indices used for tracking the ILS were the same in all three of the electronic-display conditions using the same display elements. The SV image was not being used to provide explicit guidance for the approach and, thus, was not contributing to or detracting from tracking performance. Further, pilots were constrained to execute the missed approach if they did not have the runway in sight at the chosen DH, as they were not allowed to continue below DH with the SVS. At RVR 1200 and DH 150, pilots were equally likely to execute the missed approach as to continue to land, and when they did continue, it was often because they actually overshot the DH before making the decision. One pilot's data were removed from some of the analyses due to missing or incomplete data for some of the approaches/variables.

Learning Effects. The two PFD-no-terrain baseline trials (1 and 11) were compared to assess learning effects across the approaches to KOKC. Each used the conditions of HDD PFD without terrain but containing a runway outline, 1400 ft. RVR, and 100 ft. DH. This comparison indicated that although the trend was toward improvement from the beginning to the end, the change did not achieve statistical significance for either GS or LOC RMS error and variability. Given that the shifts were not far from the threshold at .05, it is believed that a larger sample size might have demonstrated significant, albeit small, improvement over trials.

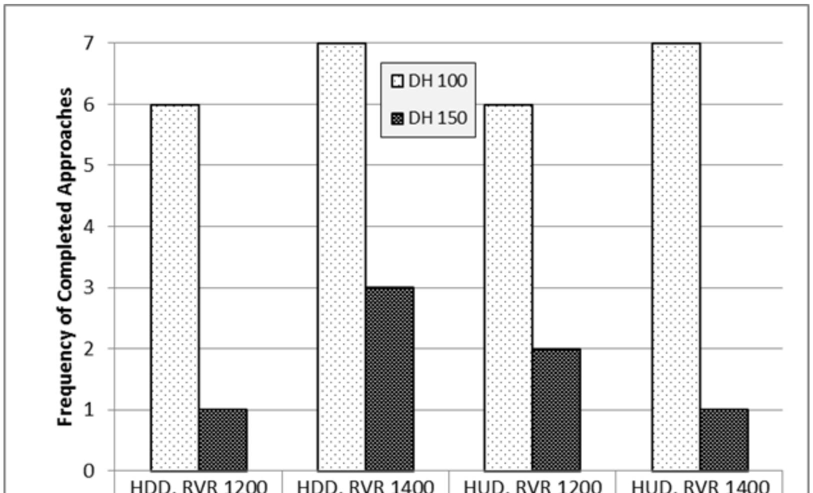
Round dial versus PFD. Another comparison of interest was what performance differences could be attributed to using a head-down Electronic PFD without terrain versus a conventional round-dial GS/LOC indicator (HSI). The three trials of interest were #1 (PFD), middle of the order (RD), and #11 (PFD). All were conducted with 1400 RVR and 100 DH to favor successful completion of the approach. It was hypothesized that the HD PFD should provide better performance by integrating the flight attitude, radar altimeter, heading, and ILS data (distance measuring equipment, DME, included) into a single display than would the separated conventional round-dial instrumentation. Comparisons between the first trial with the PFD and the RD condition did not indicate any significant differences in GS or LOC mean or variable error. Comparisons between the RD condition and the final baseline PFD trial, means shown in Table 1, did show differences for measures of variable error favoring the PFD: Glide slope RMS error (one-tailed t-test; $t(5) = 2.821$, $p = .018$), and CDI RMS error (one-tailed t-test; $t(5) = 6.433$, $p < .001$). There was no detectable difference in bias (mean) error.

Table 1. Mean RMS error for round-dial and electronic PFD reference trials.

	Glide-slope mean RMS error	Localizer mean RMS error
Round-dials	0.55306	0.32758
PFD, trial 11	0.36970	0.10504

While this difference could certainly be attributed to the integrated format being superior to the nonintegrated format, another contributor could be that the round-dial configuration was flown after several preceding trials where the pilot had used the PFD. Thus, we could also be seeing a regression of sorts, highlighting the previously observed difficulty of transitioning from electronic PFD instrumentation back to the conventional round dials.

Completed versus Missed Approaches. The conditions that allowed pilots to land consistently during the SA CAT I approach were 1400 RVR and DH 100, a combination of greater visibility and lower DH. Cochran's Q test (nonparametric) was used to look at frequency data for completed versus missed, and the effect of DH was significant ($Q(7) = 26.5728$, $p < 0.0005$). (See Figure 4.)



	HDD, RVR 1200	HDD, RVR 1400	HUD, RVR 1200	HUD, RVR 1400
DH 100	6	7	6	7
DH 150	1	3	2	1

Figure 4. Frequency of completed approaches/landings by DH, RVR, and display type.

Comparing the three baseline (no SV) conditions flown in 1400 RVR with a DH of 100, the two trials flown with the PFD had a high probability of successful completion (T1 at 0.83 and T11 at 1.00), whereas the trial flown with the round-dial configuration had only a 0.33 success rate. Participants were 3 times more likely to complete the last approach with the PFD than they were using the round-dial configuration.

Descent below DH. Another concern was how far pilots descended below DH prior to arresting their descent on a missed approach. All trials with a go-around to missed approach were separated by category and variable level and the mean, minimum, and standard deviation were calculated for each. If one examines the mean performance across display types, the average descent below DH was less than 10 feet for all displays. An extremely unequal n prevents much more than descriptive statics from being used–there was only one missed approach, for example, in the HDD without Terrain condition.

However, the extremes (minimum altitude or maximum descent below DH) were about the same for the round dial and the head-down displays, and slightly less, though not significantly, for the HUD (Figure 5). Similarly, mean and variation were about the same between a DH of 100 and one of 150 (again, very unequal sample sizes), but the maximum deviation, which will always be for one participant only, was greater in the DH 100 condition (69 feet). Finally, RVR did not appear to have an appreciable impact on either the mean descent below DH or the maximum deviation.

Thus, for the SA CAT I approaches, display format was less important than were RVR and DH. It should be noted that a RVR of 1000 ft. with a DH of 100 ft. always caused a missed approach in pretest, so that condition was dropped from the main experiment.

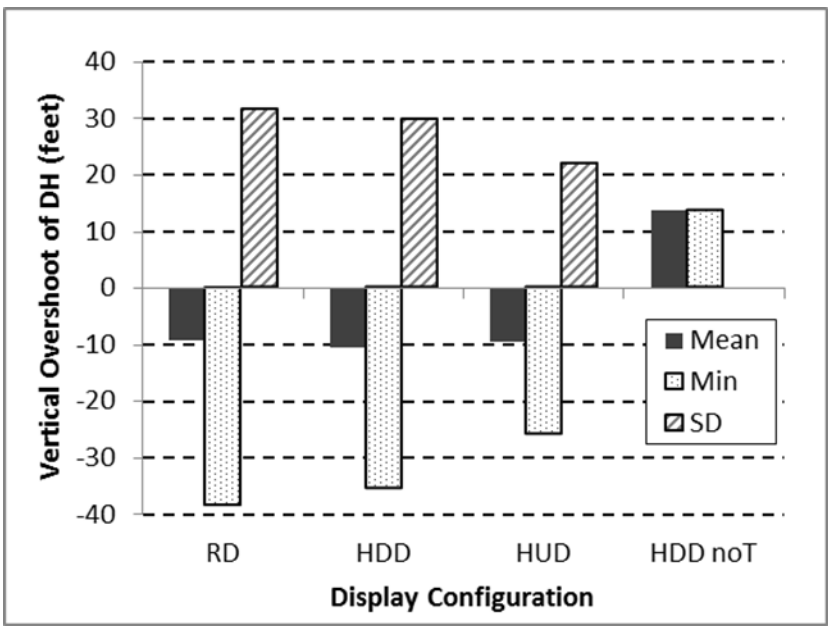


Figure 5. Mean, minimum, and standard deviation for descent below DH by display type where RD = round dial, HDD = head-down display, HUD = head-up display, and HDD noT = head-down display without terrain.Task 2, Full-mission simulation from KEGE to KASE

LOC and vertical-path error. For the approach to KASE followed by a missed approach there was, again, little variation on the approach side, excepting where there was a late turn to intercept the inbound LOC or an overshoot of top of descent. There was considerable variation within participants on the missed approach/departure, which was the main focus of this task (see example in Figure 6). The most significant error observed was incorrect setting of the outbound heading on the HSI resulting in reversed sensing. Pilots needed to select the inbound heading to that LOC to have correct left-right deflection shown on the HSI. Some pilots selected the outbound heading and tried to fly to the needle, became disoriented, and required assistance. The track widely separated from the others on Figure 6 represents a misselected heading.

Despite occasional outbound tracking problems, all participants managed to adequately clear the ridge line west of the airport on the missed approach, all means being over 600 feet, which was considered to be a potential benefit of having synthetic terrain depicted on a display. No systematic differences were seen, however, attributable to display format. Order effects appeared to be present in procedural performance as the two later trials appeared to regularly benefit from experience on the first trial. Evaluations of distance traveled to the south of the departure end of the runway during the missed approach (mean range .23 to .42 miles) indicated no reliable effect of display format on either variable, and only one pilot on one trial reached the foothills south of the airport during the turning climbout.

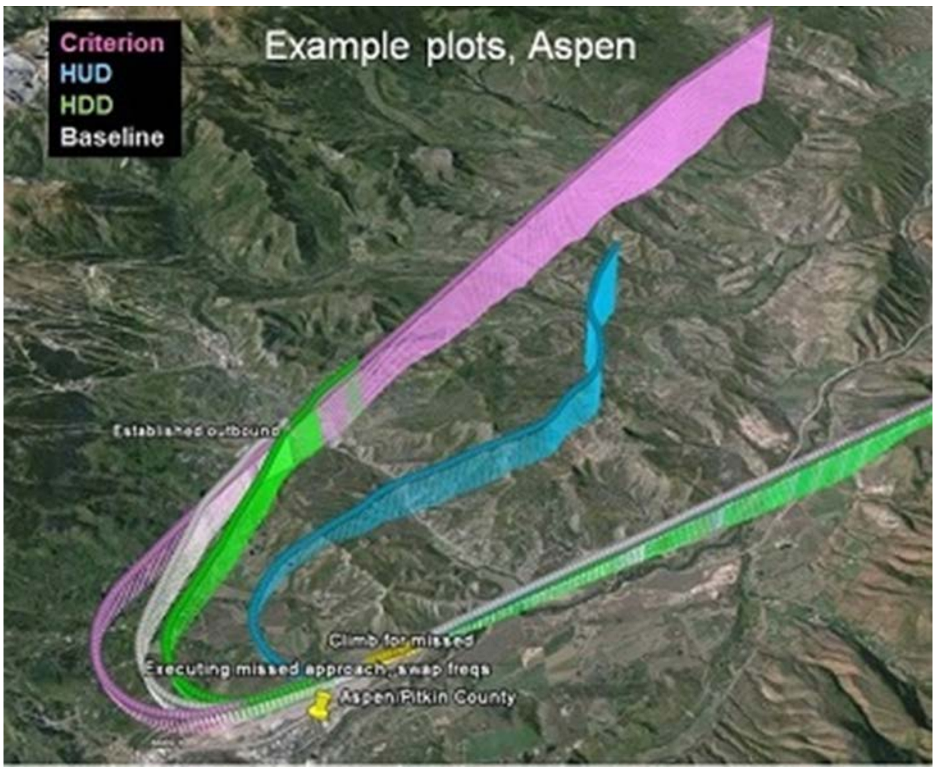


Figure 6. One set of tracks, one individual, for approaches to Aspen/Pitkin County showing the criterion track (magenta) and the three experimental trials.

Questionnaire data

Preferred features and noted problems. The most frequently mentioned useful features of the PFD in descending order were: (1) Flight-path marker, (2) Terrain (SV), (3) runway outline, followed by Radio Altimeter and glide slope. The most frequently mentioned problems were: (1) Pitch scale on PFD during missed approach and, (2) HUD runway outline obscuring real runway image. The feature not present but that was most frequently requested was highway-in-the-sky (HITS) guidance for both the approach and the missed approach. All pilots preferred the SVS and supported that by stating that they believed that they could operate safely to lower minima with this equipment. As seen in Figure 7, the more features that were added (in the order PFD, flight-path marker, radar altimeter, and terrain), the lower minima the pilots stated they were willing to accept.

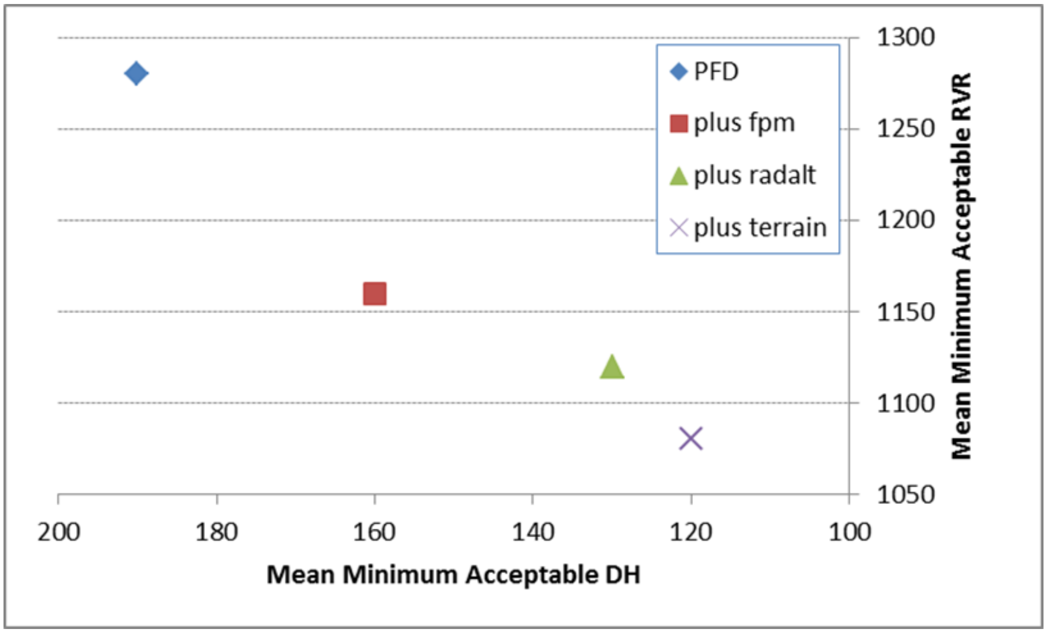


Figure 7. Means of responses to the question regarding what minima pilots would accept for each addition to the basic HMD with PFD equipment configuration.

It is important to note that the participants were NOT allowed to continue the approach below the stated DH for that trial even if they felt that the SVS image was reliable enough to allow them to descend further. Thus, we do not have a clear performance-based picture of what pilots could have done using self-imposed limits, but only of what pilots (1) will do with the specific minima imposed and (2) what they think they could accept as minima given full equipage with what they had used. However, previous data from operational demonstrations have already illustrated that it is possible to complete landings in the lowest of these visibility combinations using SV-equipped aircraft.

Preferred form of SVS instruction. All participants believed instruction should be required, and the order of preference is shown in Table 2, computer-based instruction being the most preferred (1 = most preferred, 5 = least preferred)

Table 2. Mean rankings for order of preference for SVS instructional methods.

Computer-based instruction	2.29
Classroom	2.86
Video	3.00
Internet	3.29
Handbook	3.57

Limitations

One should keep in mind that certain aspects of this procedure did not represent what we would have considered optimal configurations of the cockpit systems. First, there was no SVS–related explicit guidance for the approaches or missed approaches, which is to say no highway-in-the-sky presentation was included on the displays to provide an additional path reference relative to the SV depiction. The intent was to separate contributions of SV imagery from SV-based guidance. Second, the HUD was conformal and, as such, did not maintain terrain within the bounds of the display upon best climb for this platform (a problem noted and solved in several different ways in multiple systems in the field). Finally, pilots were not allowed to continue descent to whatever DH they deemed safe given the visibility conditions and their confidence in the SV display, but had to conform to the DH values provided for each approach. Thus, it is likely that a slightly higher percentage of approaches would have been completed had the pilots been allowed to continue beyond the DH for that trial (consistent with their comments).

Phase 1 Summary and Conclusions

This exploratory investigation was intended to determine what levels of GA pilot performance could be expected with a SVS combined with conventional attitude information overlays across variations in RVR and DH. The aim was to provide information to inform the determination of allowed credit for SVS equipage for instrument approaches. The data suggest that the presence of SV can increase the confidence that pilots have and influence the altitude AGL to which they believe they can descend as additional features are added to the system, meaning, on average, down to a practical DH of 120 feet with a RVR of just over 1000 feet. Further evaluations are needed to assess precisely to what DH and RVR combinations operational credit can be extended in actual operation, especially if SV-linked guidance is present, which is, of course, dependent upon the flight platform involved and, as such, representative time and altitude AGL needed to successfully arrest a descent and execute a missed approach.

Results indicated that the ILS tracking performance into KOKC was not reliably differentiable by display type, but the frequency of go-arounds was influenced by DH and RVR, specifically that the higher DH, 150 feet, exerted primary causality on pilots going around with RVR, 1200 feet, being a weaker and secondary influence. It was also apparent that pilots were willing to fly to lower DHs with lower RVRs as the equipment they would be allowed to use was "increased" to include more features/functions, despite a rather equivocal performance outcome.

Following the conclusion of Phase 1, the HMD was designed and fabricated from component parts, additional computers were interfaced with the simulator, scene and instrumentation programming was completed and tested, and preliminary pretesting conducted to verify function. Phase 2 was, for all intents and purposes, a replication of Phase 1 but using the HMD as the comparison display.

Method – Phase 2

Experimental Design

The experimental design, tasks, and variables were the same as in Phase 1 with two exceptions.

- Displays (2) used were the HUD with SV (common to both phases) and the head-mounted display (HMD) with SV
- The baselines (3 trials) were

- Two trials, beginning and end, using the HUD with no SV
- One trial, in the middle of the order, using the HMD with no SV

Equipment

The same flight simulator as used in Phase 1, a Piper Malibu/Meridian (Figure 8) with the same HUD as previously (as seen in Figure 2B), a head-mounted/worn display (HMD, Figures 8 and 9) providing electronic Primary Flight Information, and an electronic moving map, served as the research platform. However, in the HMD the terrain could be depicted in either of two formats; one was a full-color textured version (Figure 10) and the other was a wire-frame representation (Figure 11) with monochrome constant-brightness shading within the grid boundaries.

Figure 8. The Advanced General Aviation Research Simulator (AGARS) configured as a Piper Malibu/Meridian with the HUD stowed and pilot using the HMD.

Figure 9. Pilot wearing LUMUS derivative HMD.

Figure 10. View through the HMD showing the full-color textured/shaded terrain.

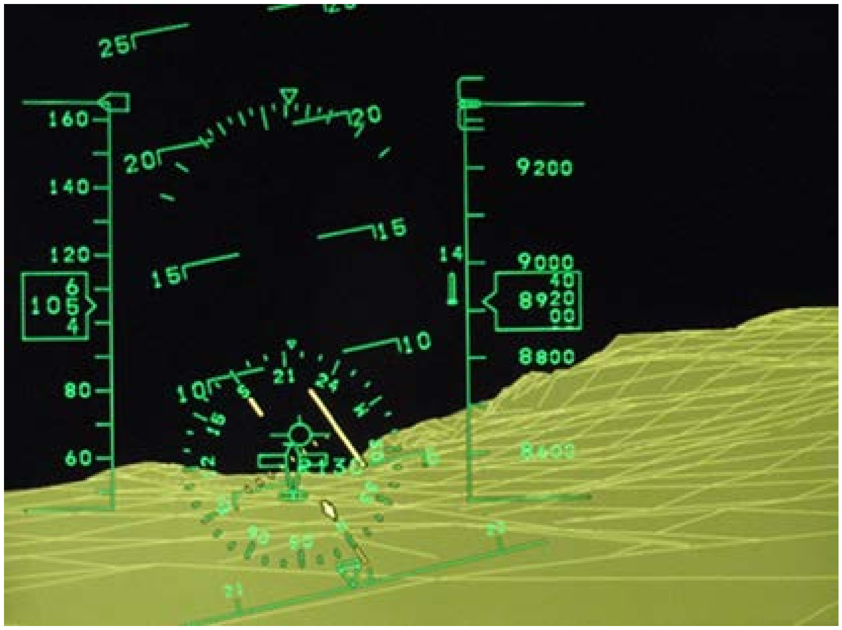


Figure 11. HMD wire-frame version of terrain image.

It should be noted here that in pretest and early trials with the HMD, it was found that the displays suffered from color/brightness range compression. Specifically, the brighter features (peaks, snow, etc.) in the terrain representation appeared even brighter in the HMD, while the darker areas (valleys, shadows) appeared darker than the graphical representation on a standard PC display. This was very visible in the mountainous terrain used for Task 2, but was not an issue for Task 1 given the flat nature of the terrain around KOKC (and the higher resolution of the metro model) and thus the representation lacked any unusually bright or dark (shadowed) features. Use during Task 2 caused some difficulty in interpreting portions of the SV features of the HMD, and thus the filled wire frame was brought in to overcome these particular issues, presenting a more uniform shading to the terrain and using a uniform grid for aid in spatial interpretation of the scene.

The HMD (Figure 9) was a binocular stereoptic device assembled in house from two LUMUS monocles with approximately 75% transmissivity. This approach was used in preference over the LUMUS eyeglass-form display for a number of reasons. The latter could not accommodate the wearing of eyeglasses and had substantial temple pieces that blocked side (peripheral) vision and were thus not suited for other (helicopter) simulator experimentation that we were scheduled to conduct. In contrast, as can be seen in Figure 9, no obstructions to peripheral vision were present in the HMD as constructed from these two monocles (the wave-guide displays had no frames), and there was no disproportionate weight placed upon the bridge of the nose (all weight carried by headband). The displays were comparatively high resolution (800 x 600) and each eye display spanned approximately 26 degrees of lateral visual angle. The inter-pupillary distance (IPD) was adjustable as was the vertical positioning of the displays. Each display was driven by a separate Image Generator, each of which was driven by a single host machine that processed head-position input and justified the viewing vector accordingly.

Participants

Twelve local male instrument-rated GA pilots participated in the study. Median age was 29.5 years (range, 20 to 48), median years flying was 13 (range, 1 to 25). Median hours total flight time was 1230 (range, 230 to 3600). Five had limited or no experience with electronic flight displays and the other seven had used Garmin, Aspen, or Avidyne systems.

Tasks

Tasks were either the same as in Phase 1 (i.e., Task 1) to facilitate a direct comparison with those data or slightly modified (Task 2) or added (Task 3) to specifically examine capabilities unique to the HMD.

Task 1 (primary) SA CAT I approach. This task was the same as that performed in Phase 1, the SA CAT I approach to KOKC, runway 35R.

The modified Task 2 and added Task 3 were not directly related to immediate concerns about operational credit, but were suggested by previous predictions of where General Aviation technology was likely headed, now realized (Beringer, 1999), and the technical possibilities of what a HMD could offer (unrestricted viewing of a simulated external environment overlaid with synthetic navigational cues). These concepts had been demonstrated in other studies, particularly those involving rotorcraft applications (Beringer, Luke, Quate, & Walters, 2009; Beringer & Holcomb, 2010; Beringer & Drechsler, 2013). Thus, this was an opportunity to gather additional data relevant to this unique display platform.

Task 2 (ancillary), Cross-country flight with approach and missed approach at destination. This variant on the Task 2 from the first phase was modified to partially replicate earlier studies in demonstrating how synthetic navigational cues (highway in the sky [HITS] and destination marker), those that might be most accessible and effective in a HMD, might assist in flying a continuous descent and executing a missed approach in challenging terrain using this display type. Pilots flew the LOC approach to Aspen, CO (KASE) (3); one with each display configuration (HUD no SV, HUD with SV, and HMD with SV). Two counter-balanced orders were used across participants. The ceiling was between 300 and 250 feet AGL, with the RVR greater than 3 miles upon breakout and DH was set at 200 feet. This is nominally a step-down approach and has only localizers (one for inbound and one for outbound on the missed approach, the latter being a back course) and no glideslope. It was flown as a Continuous Descent Operation (CDO) from top of descent to the runway threshold using the flight-path marker (FPM) as guidance in trials where the HITS was absent.

The specific advantage to using the HMD for this task was the ability of the pilot to look away from the primary longitudinal axis of the aircraft and see terrain and synthetic features not visible directly ahead of the aircraft. This provides a potentially huge advantage over the HUD as the field of view is, for the most part, restricted only to head and neck range of motion and the range of head position/orientation tracking available. This type of pilot behavior was not required, examined nor used to advantage by Task 1. The most likely clear advantage in this task would be the intercepting of the outbound localizer path on the missed approach as Aspen. The HITS track would not be visible in the HUD until the turn was nearly completed, but would be visible much earlier if the pilot looked up and to the right with the HMD. This should allow the pilot to determine if the rate of turn was sufficient, and visually track the intercept with the outbound track.

Task 3 (ancillary), visually referenced traffic pattern, HMD. This task was added to Phase 2 to examine, once again, unique opportunities provided by the HMD. Pilots were asked to attempt flying two visually referenced patterns using the HMD, one at KOKC and one at KEGE, in Instrument Meteorological Conditions (IMC - out-the-window view) but in simulated Visual Meteorological Conditions (VMC) in the HMD.

Procedure

Participants began the session completing an informed consent followed by a pilot-experience questionnaire (again, Appendix B) and then progressed to a familiarization flight in the simulator. They flew the simulator until they felt comfortable with their ability to maneuver and land and their questions about displays or tasks had been answered by the experimenter. Participants were then briefed on the first task and procedures and flew a warm-up approach to KOKC 35R. This was repeated if any difficulties were experienced with the approach or the procedure. After familiarization with the HUD, they were fitted with the HMD and the displays were adjusted for the participant's IPD and checked to be sure that the participant was achieving image fusion and that the image overlaid properly on the out-the-window view. Pilots then flew some familiarization trials using the HMD including a few approaches. The usual number of training trials was four.

Task 1. Data flights consisted of 1 baseline (HUD) trial, 4 experimental trials, another baseline (HMD), 5 experimental trials, and 1 final baseline (HUD) trial. Otherwise, all procedures for this task in this phase were identical to those in Phase 1.

Task 2. At the end of the approaches participants were asked to attempt the equivalent of a visual flight pattern at OKC using the HMD with the full-color textured terrain depicted. This was done in IMC with a ceiling of approximately 200 feet and the participants took off from KOKC, flew a left-hand pattern, and then returned and landed on the same active runway. This was followed by a visual pattern in IMC at Eagle County, an airport that has surrounding low hills on all sides. This was performed similarly to the pattern at KOKC excepting that the surrounding terrain and its elevation was discussed prior to the pattern flight and it was recommended to the pilot that the pattern should be kept in close to avoid flying in too close proximity to the hills. The latter trials in the sample all used the wire-frame format for the terrain.

Task 3. KASE segments (3; HUD, HMD, and HMD with HITS guidance) were all flown as complete missions from KEGE (Eagle County), which is to the north of Aspen, to KASE. Participants took off from KEGE, climbed to altitude (13,000 feet) while making a procedural turn (at 500 feet AGL) to the south to intercept the localizer for KASE, initiated decent at the top-of-decent radial off of the Red Table VOR, and made a continuous descent to KASE using the flight-path marker to keep the projected contact point near the touch-down zone. The actual break-out altitude was between 250 and 300 feet AGL. Upon reaching DH (200 feet), the pilot was instructed to execute the missed approach. This required an immediate climbing right turn to intercept the outbound LOC (heading 303 degrees, but set course needle to reciprocal), and a climb to 13,500 feet. The missed approach was continued until the aircraft was established on the outbound course or until the flight track had diverged sufficiently to appear unrecoverable. These KEGE to KASE flights each required approximately 15 minutes to complete.

It should be noted that a conformal HUD image was used as would be expected. This was appropriate for approach as the terrain was always visible under the nose in a descent pitch attitude. However, the terrain image dropped out of the bottom of the PFD on the missed approach (best climb angle at 12 degrees pitch up). This again suggests a need to increase pitch scale, as seen in previous experiments, for climbs and missed approaches so that the flight-path marker and top of terrain will remain within the display field of view. An adjustable vertical FOV is used by some display manufacturers, and has been seen in both HUDs (only for pitch indications in displays with no synthetic vision) and head-down displays.

One additional note on the Aspen trials is that it was found, early on, that the full-color textured terrain representation in the HMD suffered a slight disadvantage in that it suffered from brightness/color compression as a function of a slight difference between what the image generators on the high-end PCs produced (as a function of the coloration of terrain in MetaVR, the graphics package used) and what the LUMUS display drivers were able to reproduce. Thus, the peaks of mountains were made brighter in the HMD and the shadowed regions darker than in a balanced image. Participants found this presentation difficult to interpret in some instances (only near Aspen; on flat terrain without high brightness differences, meaning the OKC area, they had no difficulty with the full-color textured image), and preferred a wire-frame representation with uniform gold-ochre fill between the lines for use in the mountains (see Figure 11). This format was used with the latter three quarters of the participants.

Post-flight debriefing and questionnaire. Immediately following the final data-collection flight, the pilot was debriefed and participated in an interview and questionnaire session. The post-flight questionnaire included the following questions:

- What minima would be acceptable to you with each display configuration/equipment?
- What features of the SVS did you find useful?
- What features of the SVS did you find distracting?
- What type of training in the use of this equipment would you prefer?
- Questions about the contrast and brightness of the HMD image and obscuration of out-the-window features.

The questionnaire was followed by open-ended questions and a discussion and explanation of the goals of the study.

Results and Discussion - Phase 2

Analyses (both descriptive and inferential statistics) were performed using the data of 11 participants. The data of one participant were found, upon post-test examination, to be unusable.

Task 1 (Primary), SA CAT I flight technical error

Graphical examination of dispersion. If one examines the first half of the trials, so as to keep the graphical representations comparatively uncluttered, the comparative variation in localizer tracking can be easily visualized. This is a necessary first step to understanding where things are more or less variable and can be used to more quickly localize, geographically along the approach, the location of specific deviations.

Figures 12 and Figure 13 show views of the approach from above and looking to the north, one depicting the dispersion of tracks made in the baseline conditions for HUD and HMD where no SV (terrain, airport) representation was present in the display (Figure 12) and an equal number of approaches with exactly the same RVR/DH combinations as those in the baseline conditions, but with SV depicted on the displays (Figure 13).

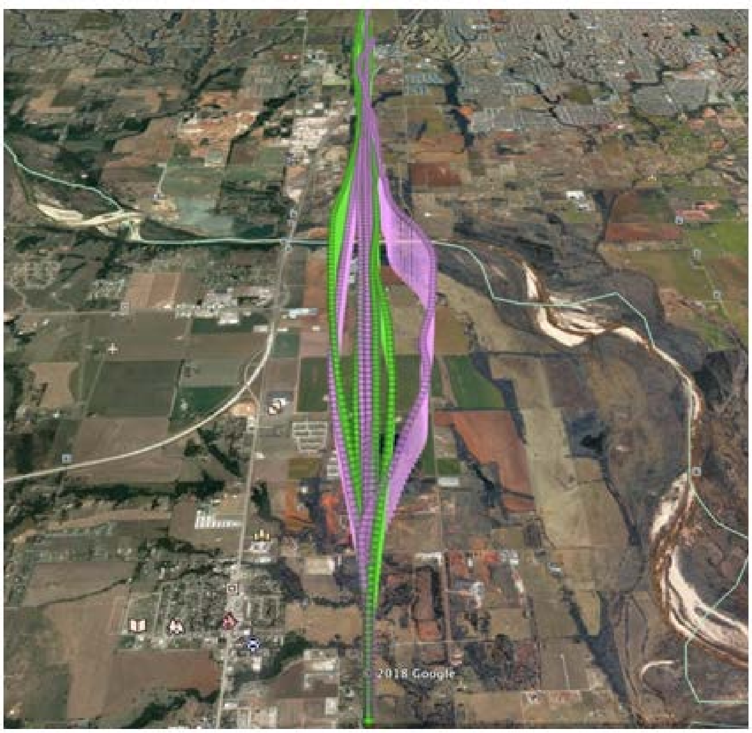


Figure 12. Track dispersion on approach with SV absent (baselines) from the displays (for Figures 12 and 13; green = HMD, magenta = HUD).

Figure 13. Track dispersion on approach with SV present on the displays.

One can see that there is a fair amount of dispersion, the most deviant one being an early trial and likely due to continuing orientation to the display being used. It is clear that the dispersion is greatly reduced from Figure 12. It should also be noted that dispersion was much greater in the first half of the approach, with the variability decreasing greatly in the second half (last 5 miles) of the approach (both figures), the part that probably matters the most. Although a part of the reduction can be attributed to the natural funneling caused by the error indications on the LOC being angular in nature, the compression appears to be greater than what could be accounted for by that alone.

RMS error for LOC and GS. The approaches were divided into three sections for further analysis. The first section, which was not subject to analysis, was that stretching from departure from the false elevated launch runway to interception of the glideslope (approximately 7.3 nm DME indication). The second section, which was subject to reduction and analysis, was that from initial intercept (not acquisition) of the glideslope to a distance of 4.0 nm DME indication. The final section was from the DME indication of 4.0 nm to DH for that approach. It should be noted that there were frequently departures from the glide-slope prior to the aircraft reaching DH. For the analyses, three categorizations were used; complete approach, far approach (7 to 4 nm DME) and near approach (4 miles to runway threshold, see Figure 14).

Analyses were performed for both constant/bias error (mean glideslope error and mean localizer error) and variable error (RMS glideslope error and RMS localizer error) for both the “distant approach” (between 7 and 4 nm from threshold) and the “near approach” (from 4 nm to threshold).

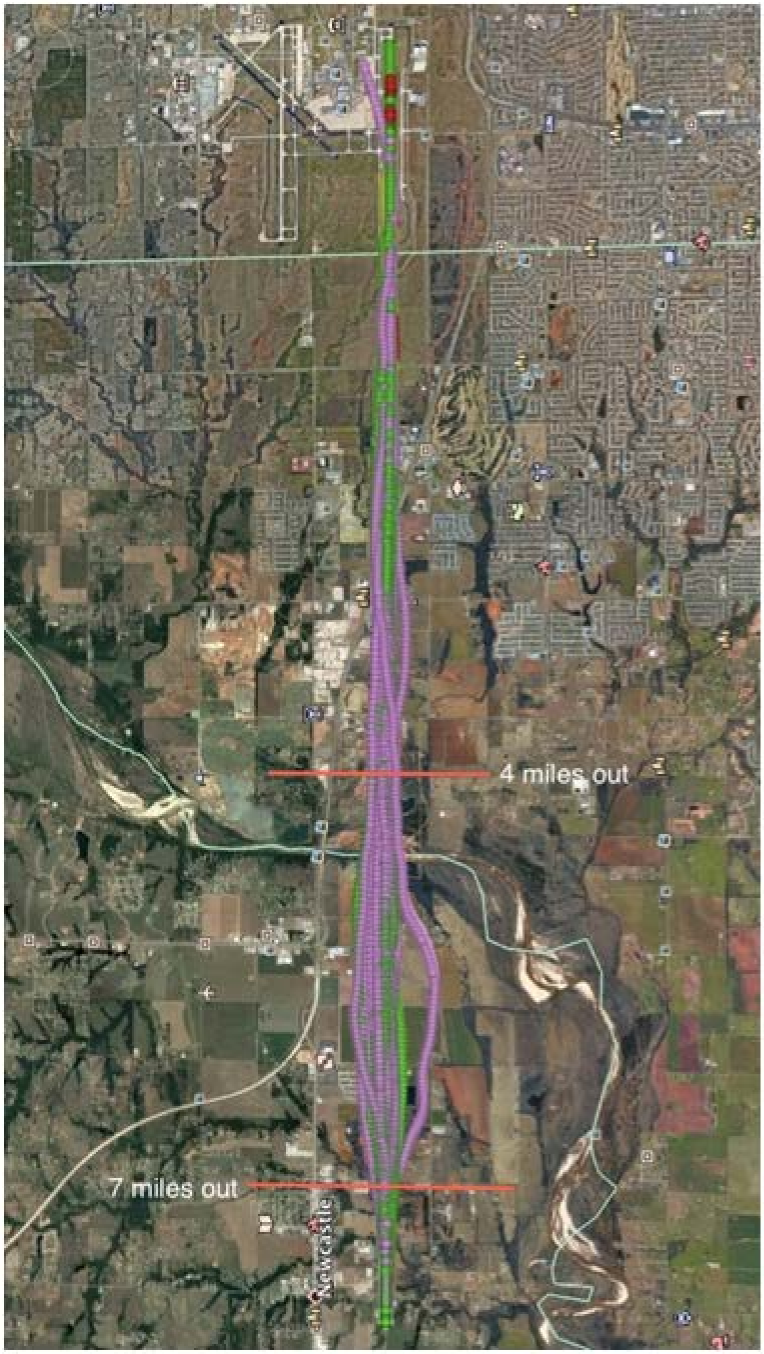


Figure 14. Dispersion across all approaches to KOKC 35R for first half of sample (green = HMD, magenta = HUD).

Distant approach. For bias/mean error, there was a statistically significant effect of RVR on glideslope error, $F(1, 69.079) = 10.468$, $p = .002$. The mean error for 1200 RVR was 0.039812 degrees and the mean error for 1400 RVR was -0.116339 degrees. However, in practice, this is a small angular error and it occurred in the distant part of the approach where there was still higher variability and pilots were attempting to acquire the ILS. Mean localizer error also exhibited a small interaction effect (RVR x DH), but there were significant violations of normality in that distribution of scores both for the Kolmogorov-Smirnov and the Shapiro-Wilk tests, and thus the test statistic was not considered to be valid.

There were main effects for display for variable (RMS) error for both the glideslope and the localizer. The mean variable error for glideslope was .28365 (in arbitrary units) for the HMD and .20992 for the HUD, $F(1, 69.572) = 4.189$, $p = .029$, which values are actually close in the larger context. Although a main effect was shown for localizer mean variable error for display, $F(1, 69.59) = 5.247$, $p = .025$, this distribution also significantly departed from normality and thus interpretation of this statistic is questionable.

Near approach. For the nearer-to-threshold part of the approach, there was a significant interaction of Display by RVR, $F(1, 67.312) = 4.428$, $p = .039$, for Mean GS error. However, this again is a result that is (1) of small magnitude and (2) suspect given that no other effects, main or interaction, were found to be significant for this variable. No effects were found for mean localizer error, and an effect for glideslope RMSe was again questionable due to a significant departure of the distribution from normality (Shapiro-Wilk test, df = 9, $p = .048$). Finally, a significant effect of display was detected for glideslope RMSe, $F(1, 67.425) = 25.686$, $p<.001$, with HMD mean = .38660 and HUD mean = .19233. Thus, there seemed to be slightly greater variability in tracking for the HMD trials regarding glideslope.

Touchdown point. It should be noted, in looking at the touchdown points for the landings, that this was a GA aircraft making an approach to a runway that was 9083 feet in length and 150 feet wide. As such, there appeared to be much less concern about precision in the touchdown location among the participants than if the approach/landing had been at a short and narrow runway. Thus, there was significant dispersion of touchdown points more so along the length of the runway than across the width of the runway. Examination of mean distance from centerline indicated a statistically significant effect of display whereby HMD landings averaged 4.65 feet from the centerline whereas HUD flights averaged 2.64 feet from centerline, $F(1, 56.445) = 4.546$, $p = .037$. Although this could be categorized as a statistically significant but operationally insignificant (2 feet) difference, one must be cautious because the sample size was comparatively small and there was a significant violation of normality for these specific data (Kolmogorov-Smirnov Test, $p = .005$; Shapiro-Wilk Test, $p = .009$).

Examination of the mean distance, along flight path, from the center of the touchdown zone indicated that both categories of flight ended with long landings relative to the nominal touchdown point, with the HMD landings averaging +323.5 feet and the HUD landings averaging +221.5 feet, a difference of 100 feet, $F(1, 56.783) = 7.411$, $p = .009$. Figure 15 illustrates the locations of these points graphically. It is worth noting, again, that there was no instruction to the participants to make precise landings at the touchdown point. They were instructed to follow the raw-data ILS guidance until visual acquisition of the runway and then land. It was also observed that participants frequently arrived at DH with a little more airspeed than was warranted, and thus tended to float long while losing airspeed before touchdown. Thus, it is questionable as to whether (1) this specific finding would be replicated in the real aircraft or (2) this is likely to have any real operational significance given that most ILS-equipped runways are long enough to easily tolerate this degree of landing long without serious consequences for the pilot/aircraft.

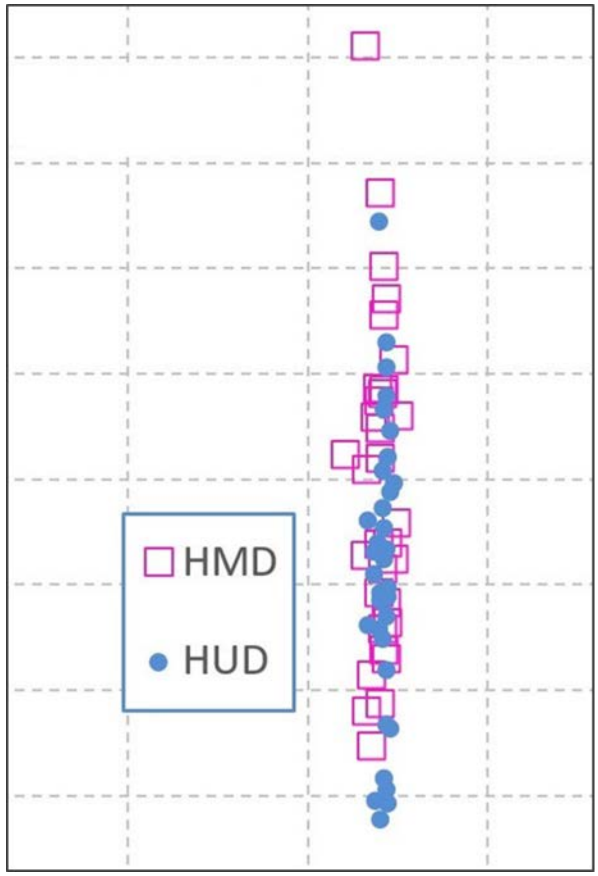


Figure 15. Distribution of touchdown points coded by display platform type (one outlier removed**).**

Learning Effects. The baseline trials using HUD were compared to assess learning effects. Two used the conditions of HUD without terrain but containing a runway outline, 1400 RVR, and 100 DH. The paired comparisons used the dependent variables DME value at glideslope intercept, mean localizer error, root-mean-squared (RMS) localizer error, distance from centerline at touchdown, and longitudinal distance from nominal touchdown zone at touchdown. These comparisons indicated that there was a weak trend toward improvement from the beginning to the end, but that there were no statistically significant differences. The weak trend appeared to be largely due to first-baseline trials being slightly more variable than not only the other baselines but also more so than the other experimental trials.

Completed versus Missed Approaches. The number of trials in which there was a go-around was extremely small and thus there was no systematic effect of the independent variables that could be determined.

Task 2 (ancillary), Cross-country flight from KEGE to KASE

Approach and missed approach. For the approach to KASE followed by a missed approach there was, again, little variation on the approach side in flight-path tracking. Vertical-path error was based upon a constant-descent reference approach from top of descent to DH as flown using the autopilot with FPM alignment with the runway as a guide. This was necessary given that there is no glideslope guidance on the Aspen approach. Any variation seen was due to a late turn to intercept the inbound LOC or overshoot of top of descent.

However, there was considerable variation within participants on the missed approach/departure. The most significant error observed was incorrect setting of the outbound heading on the HSI resulting in reversed sensing despite this having been pointed out to participants beforehand. Pilots needed to select the inbound heading to that LOC to have correct left/right deflection shown on HSI. A few pilots selected the outbound heading, and then tried to fly to the needle, became disoriented, and required an intervention/explanation.

Regardless of the occasional outbound tracking problems, all of the participants managed to adequately clear the terrain on the missed approach, which was considered to be a potential major benefit of having the synthetic terrain depicted on a display. Clear order effects were present as performance on the two later trials appeared to regularly benefit from experience on the first trial. Thus, any firm conclusions concerning a superiority of either of the display platforms are beyond the reach of these data.

Even in the presence of some order effects that affected the first trials in some cases, the HITS-assisted missed approach always exhibited the smoothest acquisition of the desired outbound track, per the example provided in Figure 16 where the central track is that accomplished using the HITS guidance.

A specific advantage of the HITS guidance in the HMD mentioned by the participants and expected a priori was that the pilots could look up and to the right to acquire the outbound corridor as far ahead as half way through the departure turn. It also provided them with an altitude target that they could ultimately align with the flight-path vector. These findings were entirely in accord with a large number of previous studies showing benefits of this form of guidance. However, these results were additionally informative as most previous examinations used a HDD or HUD primary flight display whereas our examination used a HMD.

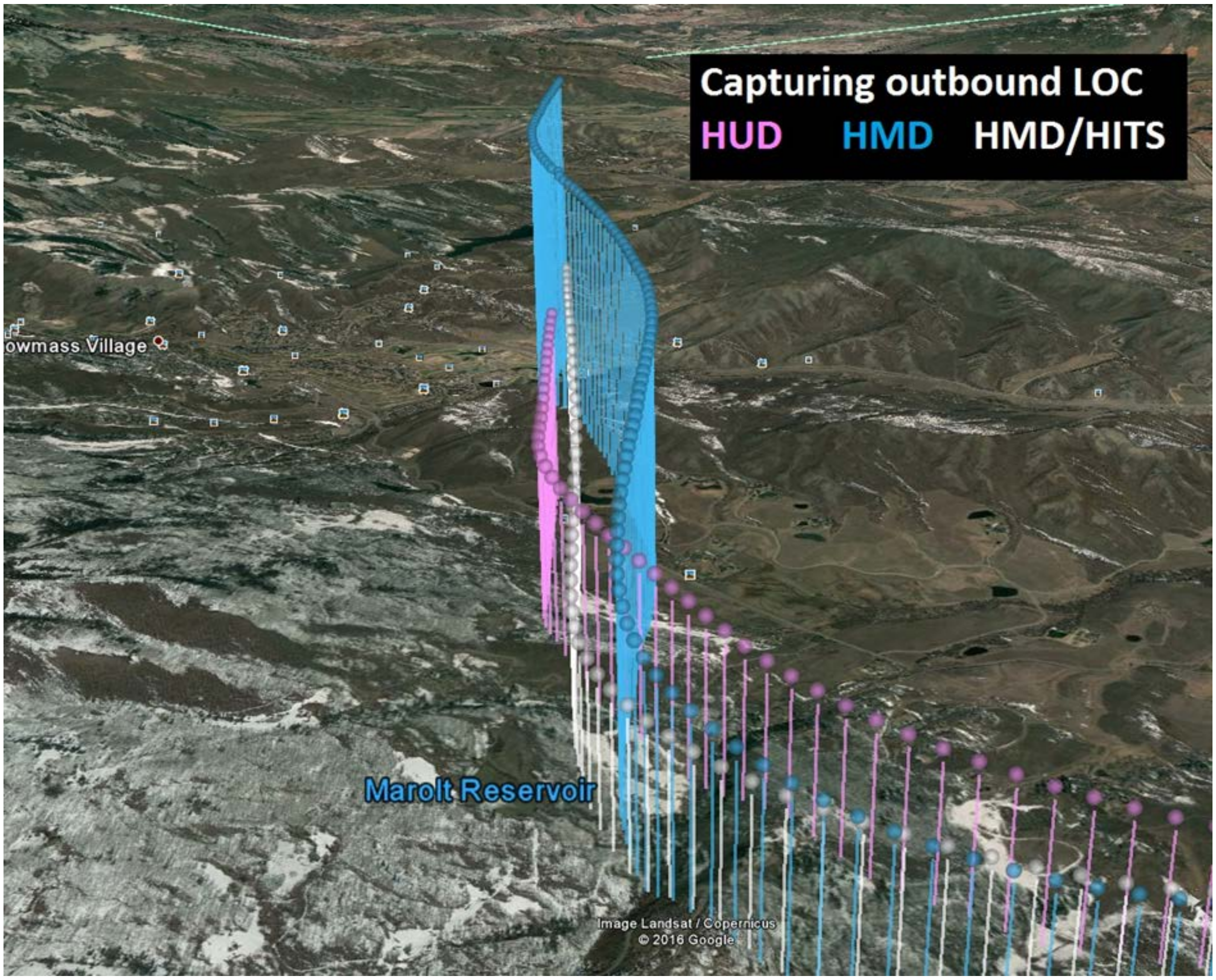


Figure 16. Example effect of HITS guidance in HMD on acquiring outbound course.

This display platform (HMD) allowed the pilots to look any-where they wanted within their range of head motion/rotation to acquire the HITS guidance cues, whereas other "fixed" displays require the pilot to wait to acquire the guidance until it enters the forward-directed field of view of the fixed display. As such, any confusion as to which way to turn to acquire the departure path when using a fixed display could ultimately result in a greater delay in locating and proceeding towards the desired flight path.

Task 3 (ancillary), visually-referenced traffic-pattern, HMD

The small number of attempted traffic patterns flown by the participants and the variability with which they flew these patterns did not produce data that was useful for statistical analyses, but it did point out some clearly observable points. The most notable of them was the tendency of the participants to regularly, across the board, overfly the intercept of the runway centerline when they were supposed to be turning to final. Looking to the left with the HMD was reported to be helpful, but not as easy as flying in VFR with direct visual contact. The biggest difficulty reported, and which was supported by pilot performance, was the accurate estimation of when to initiate the turn from base to final.

A number of things may have contributed to this outcome. First, the pitch ladder and other instrumentation was fixed in the 'forward' field of view of the HMD, and was thus lost when the pilot looked sufficiently left or right. This was noted to have contributed to a few instances of loss of altitude or attitude awareness and increased variability in altitude control. Second, the runway image and surround did not possess the level of texture and detail that one would see in the real world, which may have contributed to difficultly in estimations of relative location. Finally, pilots were frequently observed to descend below pattern altitude prematurely, thus increasing the difficulty of an accurate perception of the angle to the runway due to runway-image foreshortening and other visual factors.

Questionnaire data

Preferred features and noted problems. The most frequently mentioned useful features of the synthetic vision in descending order by number (of 11) mentioning were: 11 mentions of runway image, 10 mentions of terrain, followed by flight-path marker, 360-degree view capability (by turning head with HMD), and radio altimeter. The most frequently mentioned problems were: 6 mentions of SV full-color terrain representation, 5 mentions of HMD transport delay (lag), and 3 mentions of display clutter. The compass rose at the bottom of the HMD field of view was frequently cited as clutter in the way of acquiring the runway image in the HMD and a redesign or relocation of the data was suggested. The feature present only for one Aspen approach but requested for full-time use on all approaches (and missed approaches) was HITS guidance.

Acceptable DH as a function of equipage. Pilots were also asked to what altitude AGL they would be willing to descend on an approach as features/functions were added to the basic HMD with PFD symbology only. As seen in Figure 17, the more features that were added (in the order flight-path marker, radar altimeter, and terrain), the lower minima the pilots stated they were willing to accept. This mirrors the data from Phase 1 (Figure 17).

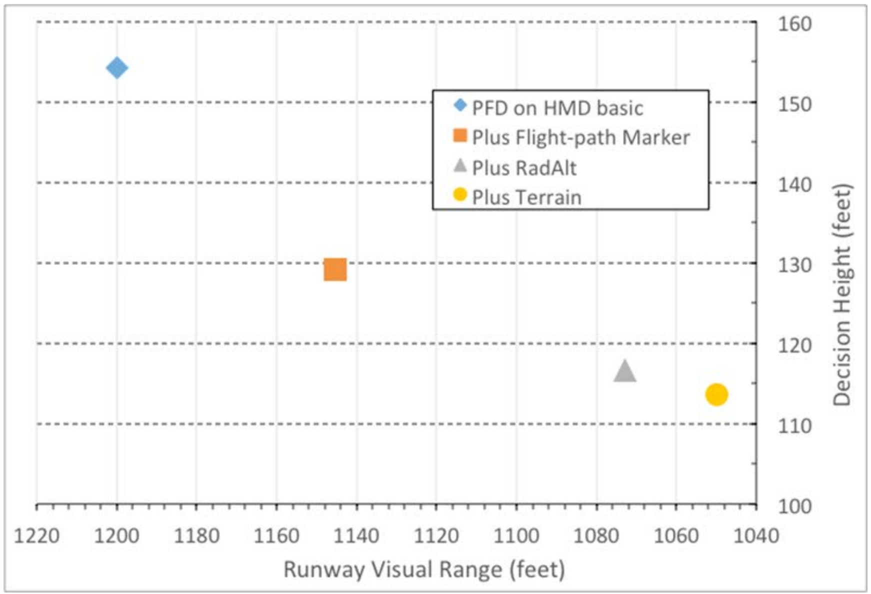


Figure 17. Means of responses to the question regarding what minima pilots would accept for each

addition to the basic HMD with PFD equipment configuration.

Per the procedure used in Phase 1, participants were NOT allowed to continue the approach below the stated DH for that trial even if they felt that the SVS image was reliable enough to allow them to descend further. Again, we thus do not have additional data regarding what pilots could have done using self-imposed limits, and the data presented are subject to the same limitations as indicated for the Phase 1 results.

Preference for terrain representation. Participants were asked about what terrain representation they preferred in the HMD for Tasks 2 and 3. Recall that the filled wire-frame version was added early in Phase 2 as a means of disambiguating the terrain representation. Table 3 presents the average rankings obtained across participants. As expected, the participants favored the filled wire-frame representation for use in mountainous terrain for the reasons discussed previously.

Table 2. Mean preferences for style of terrain depiction in HMD, mountainous terrain.

Terrain format	Mean preference (1 = most, 3 = least)
Fill wire-frame terrain	1.4
Textured terrain	1.6
No terrain	3.0

Options for manipulating the SV image. Pilots adopted various means of looking past or around the SV imagery if and when they felt they needed to. The two most notable were that they would (1) tip their head up and look under the displays or (2) rotate their head left or right to allow one eye to look between the displays and the other to the outside of the other display. 20% of participants said that they would be willing to use this means of decluttering what was in their field of view if necessary. All of the participants wanted an option to manually turn off the SV image when they felt it was necessary. This could lead to discussion of an algorithm to determine when to suppress the image based upon task needs. Ability to manipulate brightness was also mentioned as a desired option.

Preferred form of SVS instruction. All participants believed instruction should be required, and the order of preference is shown in Table 3, flight-simulator-based instruction being the most consistently preferred (1 = most preferred, 6 = least preferred), and handbook/POH being the least preferred.

Table 3. Mean rankings for order of preference for HMD/SVS instructional methods.

Means of Instruction	Mean preference (1 = most, 6 = least)
Flight Simulator	1.33
Classroom	3.25
Internet	3.42
Computer-based Instruction	3.50
Video	4.08

Means of Instruction	Mean preference (1 = most, 6 = least)
Handbook	5.42

Limitations

One should keep in mind that certain aspects of this procedure did not represent what we would have considered optimal configurations of the cockpit systems. First, there was no SVS–related explicit guidance for the approaches to KOKC and there was no flight-director symbol. The approaches were flown using raw data and a flight-path marker. Only in a few exploratory trials with a few individuals was HITS guidance available on the SA CAT I approaches. On the other hand, 33% of the approaches to Aspen had HITS guidance for both the constant-descent approach and the missed approach, where the latter was shown to support far superior performance. The intent specifically, for the KOKC approaches, was to separate the contributions of SV imagery from SV-based guidance.

Second, the HUD was conformal and, as such, did not maintain terrain within the bounds of the display upon best climb for this platform (a problem noted in previous research and solved in several different ways in multiple systems in the field), which was only a problem for climbs over significant terrain (never a problem on approach). Finally, pilots were not allowed to continue descent to whatever DH they deemed safe given the visibility conditions and their confidence in the SV display, but had to conform to the DH values provided for each approach. Regardless, the number of missed approaches was very small. Thus, despite the extremely small frequency of missed approaches seen, 1 in the first 48 approaches (far smaller than in the previous study using HUD and HDD) it is conceivable that not a single missed approach would have been seen had the pilots been allowed to continue beyond the DH for that trial (consistent with their comments).

It should also be kept in mind that some of the difficulties seen in pilots' abilities to discriminate between the HMD full-color imagery and features in the outside world were possibly attributable to both sources of visual input being CGI (computer-generated imagery). That is to say, the representation of the outside world and the SVS imagery in the HMD were being generated from the same graphical database and thus the two may have been less discriminable than would have been CGI and the real external world when both were visible to the pilot.

Conclusions – Phase 2

The Phase 2 exploratory investigation was intended to determine what levels of GA pilot performance could be expected with a SVS combined with conventional attitude information overlays, in a HMD versus a HUD, across variations in RVR and DH and was a continuation of a previous comparison of HUD and HDD. The data suggest that the presence of SV on either of the two display platforms can increase the confidence that pilots have and influence the altitude AGL to which they believe they can descend as additional features are added to the system, meaning, on average, down to a practical DH of 120 feet with a RVR of just over 1000 feet. Despite some differences in the variability of ILS tracking between the two display platforms during the SA CAT I approaches, it should be noted that pilots approached and landed successfully with each type of display.

General Conclusions

In each phase of the study, pilots were able to successfully accomplish the required approach task (Task 1) with the proposed alternate display platform (HDD in Phase 1, HMD in Phase 2) under the conditions of interest. The indices of desired performance were essentially the same across the displays (raw-data indications for LOC and GS), and thus the similarities in performance were not surprising. Differences seen in success rate (completed landing) were more influenced by the DH than anything else, and that effect was consistent across displays. It is possible that performance could be further improved through the use of other types of error indication that take advantage of the forward-looking-perspective-view display format and can be integrated into that context (SV-linked guidance).

Further evaluations are needed to assess precisely to what DH and RVR combinations operational credit can be extended in actual operation (especially if SV-linked guidance is present), which is, of course, dependent upon the flight platform involved and, as such, representative time and altitude AGL needed to successfully arrest a descent and execute a missed approach. Further, it is necessary to view these results conservatively, because the formatting of the HMD symbology was such that it replicated, to a large degree, what would be seen in the HUD and did not take full advantage of the HMD display platform by optimizing the display format for that means of presentation.

It is important to note that simulated zero-zero landings using SV (and SVGS) in actual aircraft have been demonstrated before, some concept demonstrations as early as 1988. Thus, it has already been determined what can be done when accuracy of the SVS is high and pilot skill level is appropriate. The questions remaining are ones of (1) how much error can be tolerated and to what degree that will affect DH and RVR allowances for credit (for which we have some data already), (2) what level of training is likely to be required in combination with equipage to merit operational credit, and, for aircraft capable of supporting it, (3) to what degree advances in Enhanced Vision Systems (sensor based) will moderate or combine with the use of SVS (FAA, 2010; Foyle, Ahumada, Larimer, & Sweet, 1992) in the context of combined-vision displays.

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References

Beringer, D. B. (1999). Innovative trends in general aviation: Promises and problems. In D. O'Hare (Eds.), *Human performance in general aviation* (pp. 225-261). Farnham, UK: Ashgate Publishers.

Beringer, D. B. (2016). An exploratory evaluation of general aviation pilot performance and preferences using synthetic vision displays for approaches and missed approaches in flat and challenging terrain. *Proceedings of the Human Factors and Ergonomics Society Annual Meeting, 60*(1), 76-80.

Beringer, D. B., & Ball, J. D. (2009). Unknown-attitude recoveries using conventional and terrain-depicting EADIs: Difference testing, equivalence testing, and equivalent level of safety. *The International Journal of Aviation Psychology, Special Issue on Synthetic Vision, 19*(1), 76-97.

Beringer, D. B., & Drechsler, G. (2013, May). Enhancing helicopter-pilot obstacle avoidance using a binocular head-mounted display. In *17th International Symposium of Aviation Psychology* (pp. 500-505). Dayton, OH: Wright State University.

Beringer, D. B., & Holcomb, K. (2010). Factors influencing the effectiveness of simple obstacle-related graphical depictions for head-mounted displays. *Proceedings of the Human Factors and Ergonomics Society Annual Meeting, 54*(1), 75-79.

Beringer, D. B., Luke, T., Quate, A. & Walters, E. (2009). Helicopter pilot use of a see-through, head-mounted display with pathway guidance for visually guided flight: Observations of navigation behavior and obstacle avoidance. *Proceedings of the Human Factors and Ergonomics Society Annual Meeting, 53*(1), 26-30.

Domino, D. A., Gawron, V. J., Girbert, M., Neal, D. I., Serber, M. L., & Whitenack, L. M. (2015). *Human factors considerations for HUD/HMD* (Report No. MTR 150002). McClean, VA: The Mitre Corp.

Ellis, K. K. E., Kramer, L. J., Shelton, K. J., Arthur, J. J., III, & Prinzel, L. J., III (2011). Transition of attention in terminal area NextGen operations using synthetic vision systems. *Proceedings of the Human Factors and Ergonomics Society Annual Meeting, 55*(1), 46-50.

Federal Aviation Administration. (2010). *Airworthiness approval of enhanced vision system, synthetic vision system, combined vision system, and enhanced flight vision system equipment* (Advisory Circular No. 20-167). Retrieved from https://www.faa.gov/regulations_policies/advisory_circulars/index.cfm/go/document.information/documentID/272664.

Federal Aviation Administration. (2015). *Airworthiness approval of synthetic vision guidance system* (Advisory Circular No. 20-185). Retrieved from https://www.faa.gov/regulations_policies/advisory_circulars/index.cfm/go/document.information/documentID/1028668.

Foyle, D. C., Ahumada, A. J., Larimer, J. & Sweet, B. T. (1992). Enhanced/synthetic vision systems: Human factors research and implications for future systems. *SAE Transactions: Journal of Aerospace, 101*, 1734-1741.

Kramer, L. J., Bailey, R. E., Ellis, K. K. E., Williams, S. P., Arthur, J. J., III, Prinzel, L. J., III, & Shelton, K. J. (2013). *Enhanced flight vision systems and synthetic vision systems for NextGen approach and landing operations* (Report No. NASA/TP-2013-218054). Hanover, MD: NASA Center for AeroSpace Information.

RTCA. (2015). *Minimum aviation system performance standard (MASPS) for synthetic vision guidance systems* (Report No. DO-359). Washington, DC: RTCA, Inc.

Appendix A: Charts and reference paths

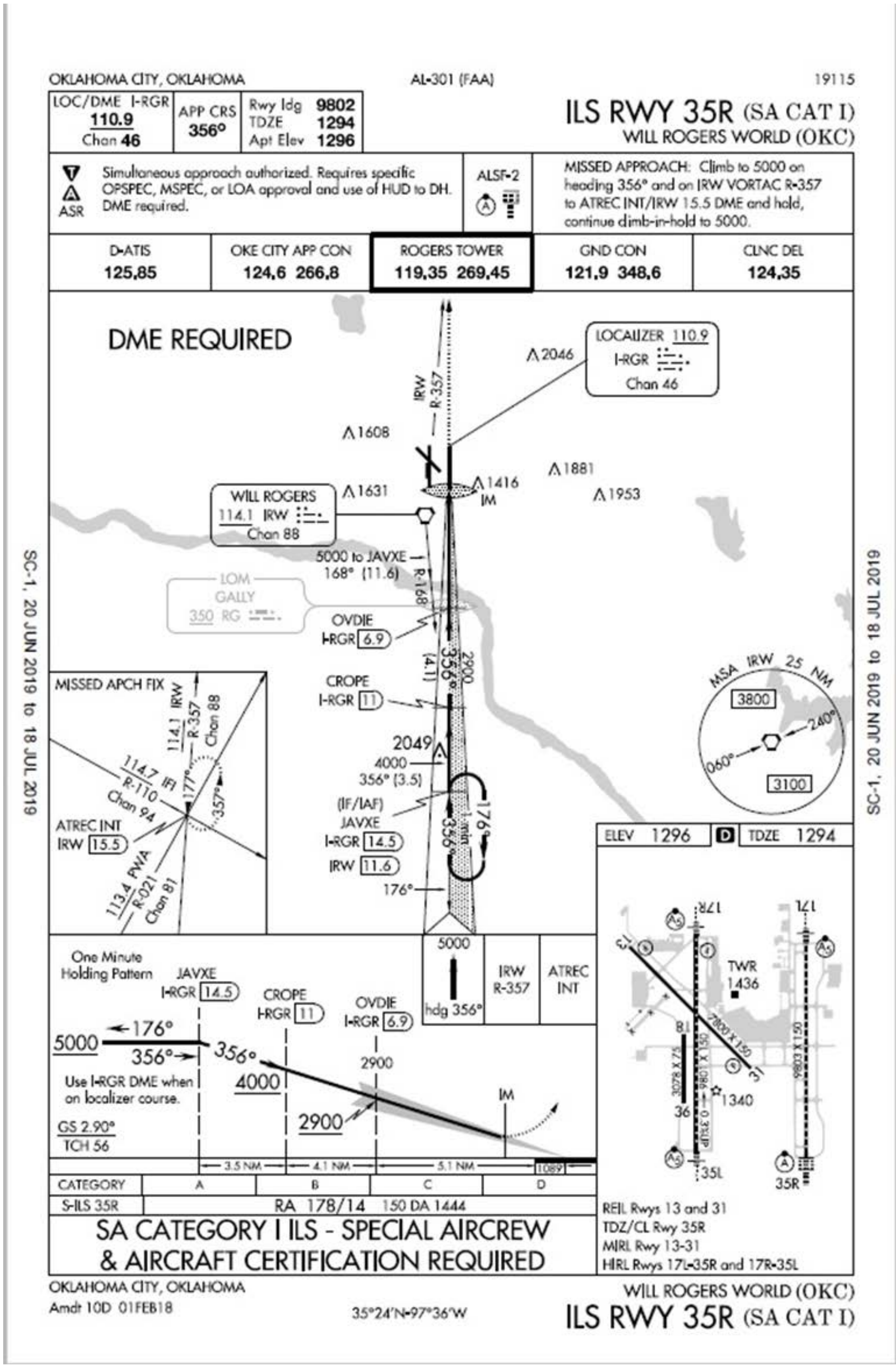

Figure A1. Approach chart for SA CAT I approach, KOKC, and ILS Runway 35R.

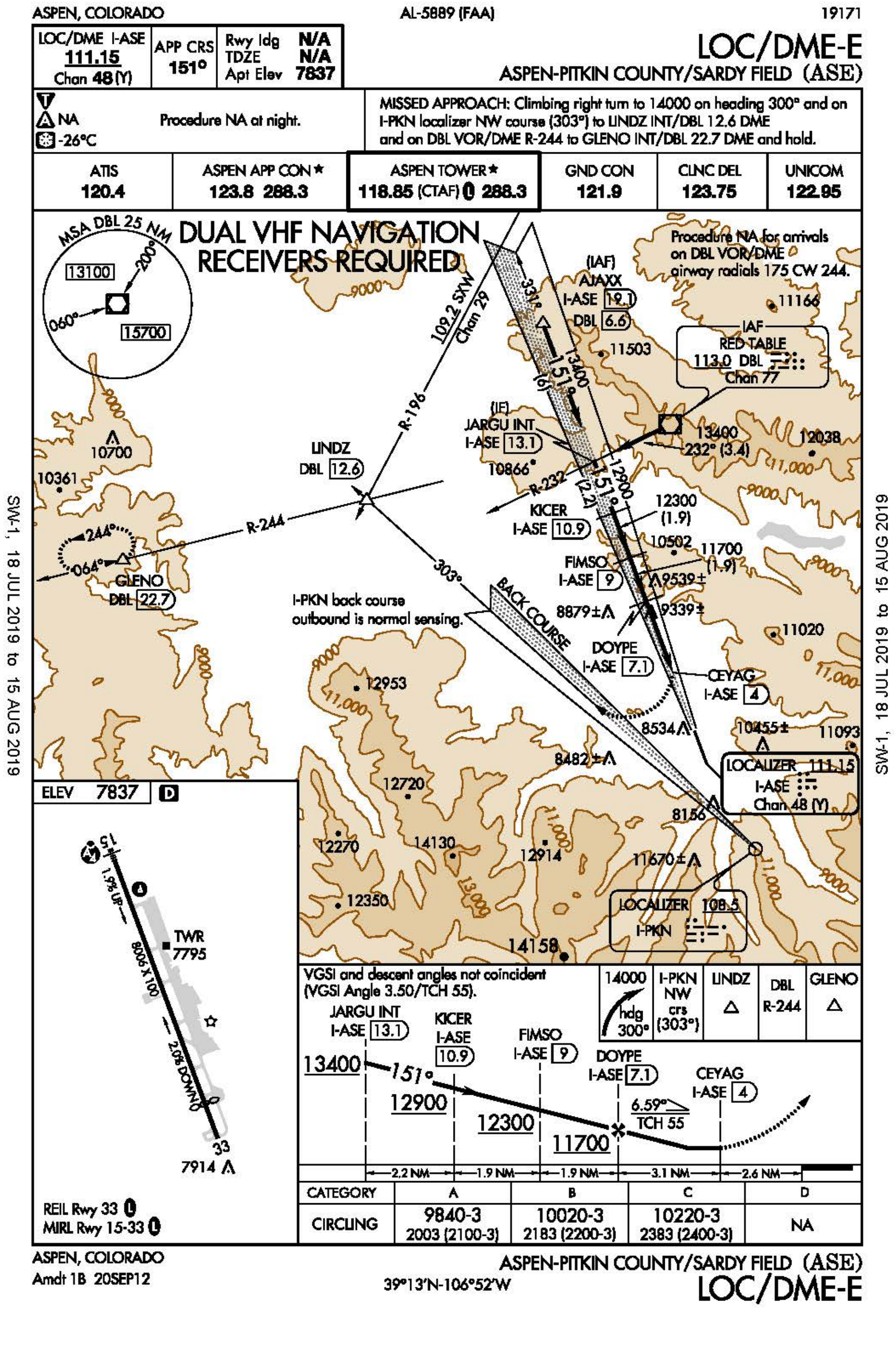

Figure A2. Approach chart for KASE, Localizer/DME-E.

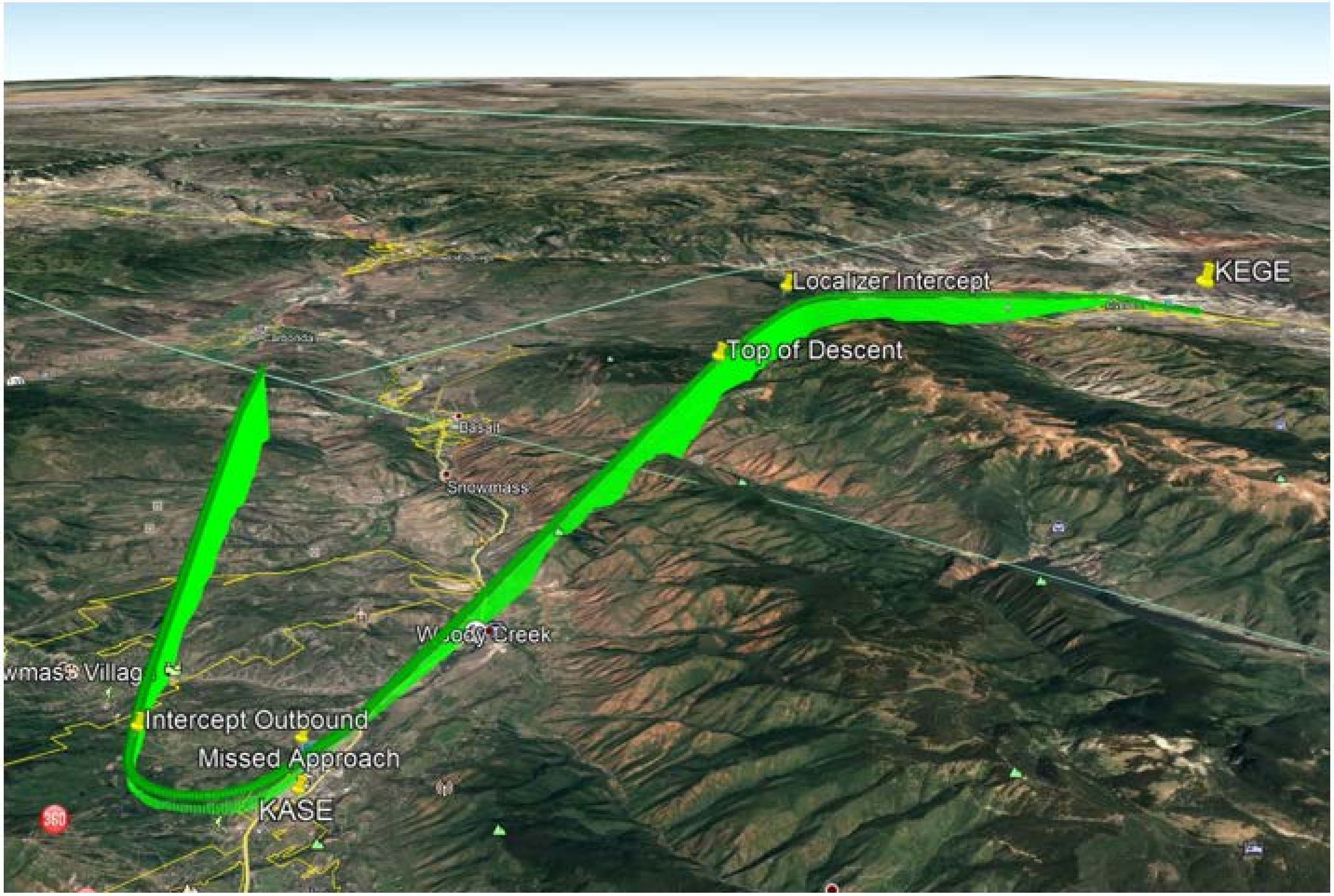

Figure A3. Plot of reference path across terrain for Task 2, both phases.

Appendix B: Pilot experience assessment

Pilot Experience Questionnaire (HMD - SVS)

It is necessary that we obtain the following data so that we can complete a thorough analysis of simulator flight performance data. All of the responses on this form will be considered confidential and will be used only to generate correlations between performance in the simulator and previous flight experience. Stored data will be de-identified such that the identity of individual participants cannot be directly associated with questionnaire responses or flight performance data. Please provide the data requested below in as accurate a fashion as possible. You may consult your log book if necessary.

1) Year that you began licensed flying: _________

2) Present age: __________

3) Sex   (M/F) ____________

4) Certificates/licenses held:
(i.e., Private, Commercial, etc.) ____

5) Ratings held:
(i.e., SEL, MEL, Instrument, ATP, etc.) _____________________________________

6) Flight hours summary (list Pilot-in-command time only):

Category of Hours	**Total in category**	**Last 12 Months**	**Last 90 days**
VFR			
Actual IFR			
Simulated IFR in aircraft			
Any flight simulator time			
All flight hours			

7) Are there any restrictions on your medical certificate? If so, please identify below -
(i.e., holder shall wear correcting lenses, etc.)

8) What was the approximate date (month/year) of your last BFR? ____/____

9) Have you flown any aircraft having electronic (NOT electromechanical) flight instrumentation? Circle the letter of any of the following that apply. For each circled item, indicate the system used and the aircraft in which it was installed/used. Include the approximate number of hours experience with that display type in the parentheses at the end of the line if you have any idea of a rough estimate. If not, indicate the percentage of your flights on which you have used any of the displays.

a) Head-down (in panel) Electronic Primary Flight Display

(EPFD)____________________(___)

b) Head-up (HUD) EPFD ____(___)

c) Electronic PFD with terrain representation
(a.k.a. "Synthetic Vision", imagery from database) ___________________________(___)

i. Approximate date of last use _________________

ii. Make or model of display/system if known ____________________

iii. Type of aircraft in which installed ________________

h) Forward-looking sensor-based display,
(e.g., infrared, millimeter wave, etc., that is sensor-based)_________________________(___)

i. Approximate date of last use _________________

ii. Make or model of display/system if known ____________________

iii. Type of aircraft in which installed ________________

10) Please indicate if you have flown any of the following display systems:

a) Chelton (now known as Cobham Systems) PFD/MFD yes / no

b) Garmin: G 420 G 430 G 530 GTN 650 GTN 750

G 600 PFD G 1000 G 2000 G 5000 (please circle each used)

c) Aspen or Avidyne avionics or other after-market retrofit electronic displays Yes / no
(Please list any other display systems that you have experience flying)

11) List Aircraft most frequently flown: (List no more than 6)

1) ______________________________

2) ______________________________

3) ______________________________

4) ______________________________

5) ______________________________

6) ______________________________

Appendix C: Structured Posttest Interview (Phase 2 version)

Pilot Opinion Interview Questions

(Head-mounted Synthetic Vision Systems)

The following questions pertain to your use of certain display features in the simulator and to your willingness to perform approaches with and without these features in the real aircraft. Please use the labeled scales to circle a response that applies to each statement in this section.

1) I would be comfortable flying under the RVR and DH conditions presented with the head-mounted display without the terrain being shown.

Strongly Disagree	Somewhat Disagree	Neutral	Somewhat Agree	Strongly Agree

2) I would fly to a DH of 100 feet AGL only if the terrain was shown on the display(s).

Strongly Disagree	Somewhat Disagree	Neutral	Somewhat Agree	Strongly Agree

3) What is the lowest DH and RVR that you would be willing to accept for each of the following equipage conditions?

a. Primary Flight Display on HMD with attitude, altitude, airspeed, HSI with LOC/GS

DH: 250	200	150	100
RVR: 1400	1200	1000	

b. Primary Flight Display on HMD with above plus flight-path marker

DH: 250	200	150	100
RVR: 1400	1200	1000	

c. (b) as above plus radar altimeter

DH: 250	200	150	100
RVR: 1400	1200	1000	

d. As above in c but with terrain shown on display

DH: 250	200	150	100
RVR: 1400	1200	1000	

4) My preference for a terrain representation on the head-mounted display would be in the following order, 1 meaning most preferred, 3 meaning least preferred (enter one of these numbers for each – use each number only once):

a. No terrain depicted on the HMD: ________

b. Wire-frame terrain on the HMD: ________

c. Textured full-color terrain on the HMD: ________

5) PFD information on the HMD:

d. The sizing of the flight-performance information in the HMD was –

i. Adequate

ii. Needed to be made smaller (went too far left and/or right) to be in continuous view.

e. The representation of the PFD fixed in the forward field of view was –

i. Ok

ii. Needed to have some features that moved with the head position (if you chose ii, circle the data items that you would want to follow head position)

1. Airspeed
2. Altitude and/or VSI
3. Some type of off-axis attitude representation
4. Other ____

6) Please list up to 4 functions, options, or features of the SVS that you found to be the most useful and indicate why you considered them useful.

a) ____________________:

b) ____________________:

c) ____________________:

d) ____________________:

7) Please list up to 4 functions, options, or features of the SVS that you found to be of little or no value or to be distracting.

a) ____________________:

b) ____________________:

c) ____________________:

d) ____________________:

8) If there are features or functions that are NOT available on the SVS you USED but that you would like to see implemented, please list them below.

9) Brightness/contrast: Please mark on the scale where you felt that each of these factors was, for you, for each of the two factors.

f.	Brightness	Too dim	Just right	Too bright	
	1	2	3	4	5
g.	Contrast	Faded into out-the-window	Ok	Obscured OTW	
	1	2	3	4	5

10) Field of view in the HMD: I thought the field of view in the HMD was –

Too narrow	Ok	Too wide		
1	2	3	4	5

11) At break-out when acquiring the runway, I would prefer to (circle a or b or write in another option):

f. Be able to turn off terrain image in the HMD
g. Tip my head up and look under the displays but leave imagery on
h. Other: ____

12) Training: What training forms would you want to see for HMD-hosted SV systems? Please rank order the following from 1 (most desired) to 6 (least desired).

Handbook (paper or electronic)	
Computer-based instruction	
Internet (on web site)	
Video (tape or DVD)	
Classroom	
Hands-on in flight simulator	

13) What operations do you believe that you could perform with the HMD-hosted SVS that would not have been possible or easily accomplished without it?

14) Do you know of any tasks/operations that could be performed using the HMD-hosted SVS that may not be allowed under the current regulations? That is, what additional operations might this technology make possible which could be considered for operational credit for future systems but are not permissible now under the operational rules?

15) Given your experience with this Primary Flight Display and the Synthetic Vision image in the HMD, please rate the synthetic terrain picture and flight-path marker for perceived overall reliability/accuracy and for their possible contributions to safety on the following scales:

Synthetic Vision – the synthetic terrain picture (wire frame)

	Poor	Below average	Above average	Excellent
Reliability/accuracy				
Safety contribution				

Synthetic Vision – the synthetic terrain picture (textured full-color image)

	Poor	Below average	Above average	Excellent
Reliability/accuracy				
Safety contribution				

Flight-path marker – flight guidance

	Poor	Below average	Above average	Excellent
Reliability/accuracy				
Safety contribution				

If you placed any ratings in the “Poor” or “Excellent” categories, please expand on which feature was responsible for that rating and why you rated it that way. Your explanation is crucial to our understanding the actual way in which pilots use these systems. How you use these systems will translate directly into how the FAA’s flight test evaluates future SVS systems.

16) Do you have a preference for one or the other form in which this display imagery can be hosted (head-mounted versus head-up display)? If you do, please indicate which you would prefer and why, including both the positive features of the one you preferred and the negative features of the one you did not prefer (i.e., advantages, disadvantages). K Keep in mind that the HMD you used is a research prototype and does not in any way resemble the proposed production models presently being evaluated by Aircraft Certification (i.e., bulk, comfort, etc. are different in the proposed production models). Primary interest is in (a) differences between seeing the imagery in a fixed HUD versus a head-referenced HMD and (b) differences between a full-color HMD and a standard-green HUD: