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Evaluation of Alternate Concepts for Synthetic Vision Flight Displays With Weather-Penetrating Sensor Image Inserts During Simulated Landing Approaches

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Summary

A simulation study was conducted in 1994 at Langley Research Center using 12 commercial airline pilots repeatedly flying complex Microwave Landing System (MLS)-type approaches to closely spaced parallel runways to compare two sensor insert concepts of “Synthetic Vision Systems” (SVS) with a more conventional electro-optical (EO) display (similar to a Head-Up Display (HUD) with raster capability for sensor imagery) flown under less restrictive visibility conditions and used as a control condition. The SVS concepts combined the sensor imagery with a computer-generated image (CGI) of an out-the-window scene based on an onboard airport database. Various scenarios involving runway traffic incursions (taxiing aircraft and parked fuel trucks) and navigational system position errors (both static and dynamic) were used to assess the pilots’ ability to manage the approach task with the display concepts. The two SVS sensor insert concepts contrasted the simple overlay of sensor imagery on the CGI scene without additional image processing (the Synthetic Vision (SV) display) to the complex integration (the Advanced Vision (AV) display) of the CGI scene, with pilot-decision aiding using both object and edge detection techniques for detection of obstacle conflicts and runway alignment errors.

The objective and subjective data results both indicate that with the scenarios employed and the display conditions implemented in the study, the SV display condition produced poor and, in several cases, unsafe performance. They also concur that the AV display produces superior performance. The safety data in particular indicate that similar SVS concepts should not be implemented without incorporating image processing decision aids for the pilot. Subjective comments indicated that the synthetic runway scene was so compelling that it was easy to ignore the sensor image information in this concept without the decision aid information.

Acronyms

ADC	analog digital converter
ARPA	Advanced Research Projects Agency
AV	Advanced Vision
AVID	Augmented Visual Display
CGI	computer-generated image
CommSW	communications software
CRT	cathode ray tube
DERP	design-eye reference point
EO	electro-optical
EVS	Enhanced Vision Systems
FAA	Federal Aviation Administration
FOV	field-of-view
HUD	Head-Up Display
ILS	Instrument Landing System
INS	Inertial Navigation System
MLS	Microwave Landing System
MMW	millimeter wave
NAV	navigation
PMMW	passive millimeter wave
PMMWALS	Passive Millimeter Wave Autonomous Landing System
RVR	runway visual range
SAL	Standard Approach to Landing
SV	Synthetic Vision

SVS	Synthetic Vision Systems
TCAS	Traffic Alert and Collision Avoidance System
TOGA	Take-Off/Go Around
TRP	Technology Reinvestment Program
VISTAS	Visual Imaging Simulator for Transport Aircraft Systems
VMC	Visual Meteorological Conditions

Introduction

Intense research efforts have been initiated within industry and the government to provide increased operational capability in low visibility weather conditions for transport airplanes (refs. 1–6). These research efforts are continuing to be developed: (1) in "Enhanced Vision Systems" (EVS), a system in which the pilot views the outside world through a transparent display (a "Head-Up" Display (HUD)) of relevant flight information (flight symbology), and which may include an image from a weather-penetrating imaging sensor; and (2) in "Synthetic Vision Systems" (SVS), a display system, typically presented head down, in which the view of the outside world is provided by a computer-generated image that may include information derived from a weather-penetrating sensor. Thus, an SVS may provide the forward view necessary for approach, landing, and surface operations under low visibility conditions by melding computer generated airport scenes (from onboard databases) and flight display symbologies with information either derived from a weather-penetrating sensor (e.g., information from runway edge detection or object detection algorithms) or with actual imagery from such a sensor.

At the time of this evaluation, raster graphics capability in avionic applications was extremely limited and research activities had been most intense for the EVS application. The SVS application, with its reliance on advanced computer graphics and an accurate and reliable database of terrain, obstacles, and the airport environment, was viewed as unrealizable in the near future. The Federal Aviation Administration (FAA) conducted the Synthetic Vision Technology Demonstration Program, a flight program to evaluate, despite the program name, EVS technologies (refs. 3 and 4). Other efforts, such as the Advanced Research Projects Agency (ARPA) Technology Reinvestment Program (TRP) on the Autonomous Landing Guidance System, continued to explore EVS potentials. Most of these efforts had emphasized flight research rather than extensive flight simulation research because of the lack of high fidelity, real-time simulation models for weather-penetrating sensors such as active millimeter wave (MMW) radars or passive millimeter wave (PMMW) cameras (inferometers).

Although raster graphics capability in avionic applications was extremely limited, laboratory graphics capability using dedicated graphics computers had become available, and pictorial display research for future applications was being explored by the display research community. Langley Research Center and TRW developed a high fidelity, real-time imaging model of a passive millimeter wave inferometer that allowed extensive simulation work in both EVS and SVS applications.[1] The subject paper used this model to evaluate several alternate concepts for SVS displays under low visibility conditions. One method for incorporating the sensor imagery into the display was to overlay the image on the synthetic scene, much as an EVS overlays the sensor image with the real-world scene. The purpose of this research was to assess that method for inserting a narrow field-of-view, forward-look sensor image into a large-screen, head-down

[1] Informal Reports:

Kahlbaum, W. M.; and House, B.: *Simulation of a Passive Millimeter Wave Sensor*. Proceedings of the Augmented Visual Display (AVID) Research Workshop, March 1993.

Passive Millimeter Wave Autonomous Landing System (PMMWALS), Final Engineering Report, TRW Space & Technology Group Report No. 59327.000, Feb. 1992.

pictorial flight display against a more computationally complex alternative.

A simulation study was conducted in 1994 at Langley Research Center that used 12 commercial airline pilots repeatedly flying complex Microwave Landing System (MLS)-type approaches to parallel runways under Category IIIc weather conditions. Two synthetic vision sensor insert concepts were used in the simulated flights, and a more conventional electro-optical (EO) display (similar to a HUD with raster capability for sensor imagery, an EVS concept), that was flown under less restrictive visibility conditions (Category IIIa), was used as a control condition.

Various scenarios involving runway traffic incursions (taxiing aircraft and parked fuel trucks) and navigational system position errors (both static and dynamic) were used to assess the pilots' ability to manage the approach task with the different display concepts. The two SVS sensor insert concepts contrasted the overlay of imagery on the scene without additional image processing (the SV display) to the complex integration of SVS and pilot-decision aiding using both object and edge detection techniques for detection of obstacle conflicts and runway alignment errors (the AV display).

Simulator Description

The Cockpit Technology Branch at Langley Research Center developed a highly reconfigurable, large-screen flight display research system named VISTAS (Visual Imaging Simulator for Transport Aircraft Systems), which was used to carry out this experiment (fig. 1). The simulator had the following elements: the Simulator Visual System (visual system hardware and graphics generation hardware and software), the Aircraft Mathematical Model, the Passive Millimeter Wave Camera Graphics Model, and the Simulator Cockpit.

Simulator Visual System

The flexible core of the visual system was embodied in dual, full-color, high-resolution cathode ray tube (CRT) projectors that were configured to vary the projected display's aspect ratio by edge-matching and overlapping the images from each projector (fig. 2). Since each projected image was 15 in. high by 20 in. wide (standard 3:4 aspect ratio), a maximum 15- by 40-in. image could be achieved. This maximum configuration was used to present the three display concepts for this investigation. The images were generated by the dual graphics display generators operating in synchronization and using the same visual database to produce a single, large-screen, integrated picture (combined by the projection system onto the rear-projection screen that served as the simulated aircraft's main instrument panel). Each generator provided image resolutions up to 1280×1024 pixels in a 60-Hz progressive scan format (per projector). Since the design-eye reference point (DERP) for transport cockpit applications is typically around 28 in., the full 40 in. wide display provided a maximum 70° horizontal field-of-view (FOV), with image resolutions approaching 40 pixels/degree across the entire display.

Aircraft Mathematical Model

A simplified six-degree-of-freedom mathematical model of a two-engine, medium weight transport aircraft was used in this study (fig. 3). The gains within the linear transfer functions were obtained empirically to represent a fixed-wing generic transport aircraft. The control system represented a basic rate command-without-attitude-hold system. Turbulence was introduced into the mathematical model through the addition of a disturbance component (a summation of eight independent sine waves) to the roll rate variable. The participating pilots considered the level of turbulence to be moderate.

Passive Millimeter Wave Camera Graphics Model

Langley Research Center and TRW developed a high fidelity, real-time imaging model of a PMMW radiometer that has allowed extensive simulation work in both EVS and SVS applications (ref. 7). A rigorous phenomenological atmospheric model of the radiometric sensor incorporated sky temperature profiles, upwelling atmospheric radiation, and rough surface apparent temperature effects to determine the apparent temperature (intensity) of each sensor element of the camera and the corresponding picture element of the sensor's display. The resulting image represented what the sensor would provide under the specified atmospheric conditions. The real-time visual scene model had the capability to vary the following sensor parameters: field-of-view, resolution (number of horizontal and vertical pixels), update rate, and various weather conditions. The sensor model used the same geographical database that is used to generate an ordinary out-the-window visual scene (e.g., terrain, runways, airport buildings, and trees). Extensive validation of the real-time program was successfully conducted by using TRW's more complex, non-real-time computer model.

For this experiment, the fields-of-view of the simulated MMW sensor were 15° horizontal and 10° vertical, with 40 pixels horizontal and 26 pixels vertical (to represent a resolution of 0.375° per pixel or 6.5 mrad). The sensor was slewed vertically and horizontally so that the center of the sensor image was aligned with the instantaneous velocity vector of the airplane, and the image was presented in a conformal manner on the display.

Simulator Cockpit

The visual and interactive control elements of this flight display research tool have been integrated as a reconfigurable piloted workstation to explore the advantages and limitations of large-screen, pictorial display concepts and associated interactive techniques. The pilot workstation (fig. 1) was configured as the pilot-flying side of a generic transport, fixed-wing aircraft with the pilot's seat designed to position the subjects so that their eyes were at the DERP. The workstation also accommodated the dual-head projection system and the rear-projection screen that simulated the instrument panel. Pitch and roll inputs to the aircraft mathematical model were provided in the workstation by a two-degree-of-freedom sidearm hand-controller with spring centering. A throttle lever provided throttle inputs. Typical self-centering rudder pedals provided yaw inputs. The display screen (instrument panel) was positioned to provide a 17° line-of-sight (from horizontal) over the top of the screen, which is typical of over-the-glare-shield views in most transport aircraft. The screen's display surface was set perpendicular to the pilot's line-of-sight.

Display Conditions

Each of the three display conditions incorporated versions of three distinct display elements: the symbology set, the PMMW image, and the outside scene. The symbology set and the PMMW image were constant, and only the outside world scene varied across the three display conditions. The ground texture used for the EO display was a realistic-looking random pattern, while the texture used for the two SVS conditions was a geometrically repetitive pattern used to remind the pilot that a computer-drawn scene was being viewed. The SVS display conditions presented an outside scene for a clear VMC (Visual Meteorological Conditions) day, while the EO condition presented the same scene with the more realistic texture and with fog, with a runway visual range (RVR) representation of 700 ft. All three display conditions used the appropriate view of the outside world presented as a 30° vertical by 70° horizontal field-of-view, forward-looking scene of the airport environment at unity magnification. Figure 4 presents a representation of the display conditions.

The symbology set (fig. 5), which was intended to represent typical HUD symbologies, included airspeed and ground speed digital readouts, barometric altitude and radar altitude digital readouts, roll and pitch scales (in degrees), a vertical speed digital readout, and a heading tape scale. The central HUD symbology consisted of a "winged-v" symbol depicting pitch attitude, a "footed-o" symbol for instantaneous flight path vector, and a "small circle" for flight director commands. The display was attitude-centered for an attitude rate command control system, although the pilots' task was to control the flight path vector. The symbology set also included a secondary "smoked-glass" (see-through) Navigation Display presented on the left side of the forward view displays that represented a conventional Navigation Display (see fig. 6).

Electro-Optical Display Condition

The EO Display Condition was intended to represent an EVS display concept in which a real-world view of the airport environment was presented to the pilot, along with the symbology set overlay and a selectable sensor image. The pilots could toggle the sensor image on/off as they wished with the trigger switch on the hand controller.

Synthetic Vision Display Condition

The SV Display Condition was intended to represent the most rudimentary implementation of an SVS. The condition simulated a computer-drawn view of the airport environment, along with the symbology set overlay and a selectable sensor image. The pilot could toggle the sensor image on/off as he wished with the trigger switch on the hand controller. The sensor implementation provided for no additional image processing within the system. As a result, the only difference between the system implementation for this condition versus the EO condition was the outside world scene. The EO condition simulated a real-world, out-the-window scene, while the SV condition simulated a pictorial format of a synthetic scene based on a stored database.

Advanced Vision Display Condition

The AV display condition was intended to represent a complex integration of the CGI scene with pilot-decision aiding using both object and edge detection techniques for detection of obstacle conflicts and runway alignment errors. Thus the only difference between the system implementation for this condition and the SV display condition was the addition of system advisories to the pilot of detected alignment errors and obstacle conflicts, as well as iconic representations within the outside scene of detected objects. A rudimentary graphics model of a B-727 was used as an iconic representation of both airborne and surface airplanes, and a rudimentary graphics model of a fuel truck was used as an iconic representation of smaller ground objects. These icons were present in both the EO Display Condition and the AV Display Condition, when appropriate.

Experimental Tasks and Schedule

Twelve pilots, all with extensive glass-cockpit experience, and most of whom were current line pilots with national commercial airlines (two were test pilots with commercial airplane manufacturers), participated as subjects in the experiment. In the overall experiment, six separate experimental tasks, induced by scenarios intended to generate differences between the display conditions, were embedded within the Standard Approach to Landing. These scenarios included an Aircraft Incursion Scenario, a Fuel Truck Incursion Scenario, a Dynamic Glideslope Error Scenario, a Dynamic Localizer Error Scenario, and two variations of a Static Error Scenario.

Standard Approach to Landing

All scenarios mentioned previously were implemented within the Standard Approach to Landing (SAL). This basic task was a simulated approach to landing about 6 nmi long, consisting of a complex MLS-type approach (fig. 7) to parallel runways (with a continuous 3° glide path). The short final approach segment was only 1.7 nmi long. The SAL and the runway configuration were constructed to provide a complex environment of sufficient duration (about 5 min per flight) for exercising the selected measurement tools. The environment was not intended to replicate the real world (although it is very similar to Denver Stapleton Airport's 8L and 8R runways), but merely to represent a somewhat realistic, demanding future environment.

The pilot's task was to fly the SAL manually (including throttle inputs) using the display condition available. The flight ended at touchdown or whenever the pilot pushed the Take-Off/Go Around (TOGA) button. The decision height procedure adopted for the experiment for all three display conditions was that procedure developed in the FAA Synthetic Vision Flight Demonstration Program (ref. 4). Before descending below a 200-ft altitude, the pilot had to make a "runway image call" announcing his assurance that the sensor image provided a view of the runway and that his situation relative to the runway was acceptable enough to continue. With the EO display condition, the pilot also made a "visual land call" before the 50-ft decision height, which acknowledged that he had acquired the "real-world" runway (through the fog). No "visual land call" was required with the SV and AV conditions.

The pilots were instructed to assume that no registration or alignment errors between the sensor image and the outside "real-world" scene would occur (i.e., the sensor image always represented the true outside world situation, as did the out-the-window scene for the EO display). However, the pilots were warned about the possibility of encountering, and were trained to recognize navigational system position errors (both static and dynamic) within the symbology set for all three display conditions and within the synthetic scenes for the SV and AV display conditions.

The Aircraft Incursion Scenario

Under all scenario conditions except the incursion scenario, a B-727 transport taxied into position and stopped at the Hold-Short line for the active runway. In the incursion scenario, the aircraft pulled out onto the runway and began a takeoff roll down the active runway. The pullout was timed so that the incurring (takeoff) aircraft would be at the touchdown point (1000 ft from the runway threshold) simultaneous to the ownships arrival at that point.

Under all three display conditions, the pilots were required to use the PMMW image to assure themselves of runway clearance. The PMMW image contained pixel information relating to the taxiing aircraft beginning at the appropriate range (with a 6 mrad resolution, about 2 nmi, or 12 000 ft). With the EO display condition, the aircraft was always present in the outside "real-world" scene, although it would not be visible until the range was less than 700 ft. To summarize the information available to the pilot concerning the taxiing aircraft while using the EO display condition, the sensor image first presented information at about 12 000 ft. The outside scene presented no information until the range was less than 700 ft.

With the SV display condition, the aircraft was never present in the outside synthetic world scene (no object detection information); so information was available to the pilot only within the sensor image, beginning at about 12 000 ft. With the AV display condition, the aircraft was present in the outside world scene after the range had decreased to 10 000 ft. (It was assumed that the object detection algorithms within the AV system would have uncovered the location and would have been tracking the movement of the taxiing aircraft by this time.) When range had decreased to 2500 ft, it was assumed that a runway incursion algorithm within the AV system would have uncovered the runway incursion, and an alert message was posted at that time. To summarize the information available to the pilot concerning the taxiing aircraft while using the AV display condition, the sensor image first presented information at about 12 000 ft. The computer-drawn outside scene presented the information at 10 000 ft, and an alert was posted at 2500 ft. The range estimates for sensor image appearance and object/runway incursion detection algorithm performances were obtained from subject matter experts conducting active research in the appropriate fields.

The Fuel Truck Incursion Scenario

In this scenario, a stationary fuel truck was located at the touchdown point on the ownship's runway. The truck was present at the beginning of the run, but it did not appear in the PMMW image as pixel information until the appropriate range was reached (with a 6-mrad resolution, about 1.5 nmi). Under all three display conditions, the pilots were required to use the PMMW image to assure themselves of runway clearance.

With the EO display condition, the truck was always present in the outside real-world scene, although it would not be visible until the range was less than 700 ft. With the SV display condition, the truck was not present in the outside synthetic world scene (no object detection information). With the AV display condition, the truck was present in the outside synthetic world scene after the range had decreased to 8000 ft. (It was assumed that the object detection algorithms within the AV system would have uncovered the location of the truck by this time.) When range had decreased to 1000 ft, it was assumed that the runway incursion detection algorithm within the AV system would have uncovered the runway incursion, and an alert message was posted at that time. Again, the range estimates used were obtained from subject matter experts.

The Dynamic Localizer Error Scenario

Although registration and alignment errors for the PMMW sensor image were disallowed for the purposes of this investigation, simulated navigational system errors within the onboard inertial navigation system were used. Figure 8 illustrates the flight path imposed by the Dynamic Localizer Error Scenario to assess performance under the various display conditions. The scenario was intended to represent a localizer beam bend condition, and the flight director and the raw localizer error symbols responded to the erroneous localizer signal.

With the EO display, both the sensor image and the out-the-window scene were unaffected by the localizer error. With the SV display, the sensor image was unaffected, but the synthetic scene was offset by the dynamic error. This implementation is equivalent to continuously updating the Inertial Navigation System (INS) position with Instrument Landing System (ILS) corrections to position ownship within the synthetic database. Similarly, with the AV display, the sensor image was unaffected, but the synthetic scene was offset by the dynamic error. However, when range had decreased to 9500 ft (allowing a 500-ft range decrease to account for some processing time), it was assumed that runway edge detection algorithms within the AV system would have uncovered the runway misalignment error, and an alert message was posted at that time (again, the range estimate used was obtained from subject matter experts). The pilot then had the capability within the AV system to toggle between the original or a continuously recalibrated INS position reference based on extracted information from the sensor scene (doing so alternately imposed or removed the offset error from the synthetic scene). If the pilot chose to leave the AV system with the new, recalibrated INS position, the guidance information, based on the new INS data, would provide guidance to the correct touchdown point.

The Dynamic Glideslope Error Scenario

Figure 9 illustrates the flight path imposed by the Dynamic Glideslope Error Scenario to assess performance under the various display conditions. The scenario was intended to represent a glideslope beam bend condition, and the flight director and the raw glideslope error symbols responded to the erroneous glideslope signal.

With the EO display, both the sensor image and the out-the-window scene were unaffected by the glideslope error. With the SV display, the sensor image was unaffected, but the synthetic scene was offset by the dynamic error. With the AV display, the sensor image was unaffected, but the synthetic scene was offset by the dynamic error. However, when range had decreased to 9500 ft (allowing a 500-ft range decrease to account for some processing time), it was assumed that runway edge detection algorithms within the AV system would have uncovered the runway misalignment error, and an alert message was posted at that time (again, the range estimate used was obtained from subject matter experts). The pilot then had the capability within the AV system to toggle between the original or a continuously recalibrated INS position reference based on extracted information from the sensor scene (doing so alternately imposed or removed the offset error from the synthetic scene). If the pilot chose to leave the AV system with the new, recalibrated INS position, the guidance information, based on the new INS data, would provide guidance to the correct touchdown point.

The Static Error Scenario

Figure 10 illustrates the implied locations of the active runway imposed by the two variations of the Static Error Scenario, which presented a static offset localizer error that provided guidance to a touchdown point actually located on either the taxiway (when the active runway was 8R) or the parking pad (when the active runway was 8L). Figure 11 illustrates the appearance of the three Display Conditions for one of the static error scenarios. With the EO display, both the sensor image and the out-the-window scene were unaffected by the static error. With the SV display, the sensor image was unaffected, but the synthetic scene was offset by the static error. With the AV display, the sensor image was unaffected, but the synthetic scene was offset by the static error. However, when range had decreased to 9500 ft, it was assumed that runway edge detection algorithms within the AV system would have uncovered the runway misalignment error and an alert message was posted at that time (again, the range estimate used was obtained from subject matter experts). The pilot then had the capability with the AV system to toggle between the original or a recalibrated INS position reference based on extracted information from the sensor scene (doing so alternately imposed or removed the static offset error from the synthetic scene, which was assumed to be located based on INS positioning). If the pilot chose to leave the AV system with the new, recalibrated INS position, the guidance information, based on the new INS data, would provide guidance to the correct touchdown point.

Schedule

Table 1 presents the full day's schedule of the experiment for an individual pilot. After being briefed on the purpose of the experiment, the details of each Display Condition, and the various Scenario Conditions to be encountered, the pilot was allowed about 20 min to familiarize himself with the handling characteristics of the airplane model in unstructured flight maneuvers. The pilot was then thoroughly trained with the standard approach task and then was thoroughly exposed to each Scenario Condition for each Display Condition. The data collection session was in the afternoon. The Display Conditions were randomly blocked across pilots, and the experimental tasks were randomized within each Display Condition. Table 2 presents an outline of a typical session, the details of which varied from pilot to pilot. Every pilot flew each Scenario Condition for each Display Condition at least once during the data collection session.

Performance Measures and Questionnaires

The primary metrics for the experiment were provided by pilot button presses during an approach. Three pushbuttons were conveniently located for pilot access aft of the throttle quadrant and were termed and labeled as the "Looks Abnormal" button, the "TOGA" button, and the "Align Toggle" button. The pilots were instructed (and practiced and were reminded during training) to push the "Looks Abnormal" button whenever they felt concerned about displayed information, and the "TOGA" button whenever they felt that they should execute a go-around procedure. The "Align Toggle" button provided a response only when the Dynamic and Static Error Scenario conditions allowed its functioning with the AV display condition.

Also, the traditional lateral and vertical path tracking performance measures were gathered during the experiment. However, these metrics were not anticipated as being of primary importance in discriminating between the display conditions for the SAL of this experiment, since the symbology set, including an active flight director, was consistent across the display conditions.

As shown in table 2, each pilot was asked to complete a questionnaire at the end of the data gathering runs for each display condition. The questionnaire probed specific items concerning the scenarios encountered with that display condition as well as a general evaluation of that display concept. After completing all runs and the display concept questionnaire for each display condition, a final questionnaire was administered that involved detailed comparisons of the three display concepts.

Experimental Results and Discussion

The scenarios under investigation were designed as tabular analysis experiments, with no intention of providing statistical analyses other than some testing for differences in mean ranges and altitudes using Student t test analyses (with significance at the 5-percent level). The objective results are presented and discussed for the "Looks Abnormal" and "TOGA" button press data across all trials and for each scenario, and some of the subjective results are discussed thereafter.

Across All Trials

There were 504 trials in the experiment, with each of the 12 pilots flying 42 approaches. For each display condition, each pilot flew 8 SALs and one of each of the 6 scenarios (one Aircraft Incursion Scenario, one Fuel Truck Incursion Scenario, one Dynamic Glideslope Error Scenario, one Dynamic Localizer Error Scenario, and two variations of the Static Error Scenario).

"Looks Abnormal" Button Presses

Of the 504 total trials, 288 were standard approaches in which none of the scenarios were activated (SALs); 72 trials involved either the Aircraft Incursion Scenario or the Fuel Truck Incursion Scenario. For the incursion scenarios, the pilots were instructed and trained to immediately push the "TOGA" button and not to bother with first pushing the "Looks Abnormal" button. Therefore, 360 of the 504 total trials were expected not to yield any "Looks Abnormal" button pushes. The other 144 trials consisted of 36 Dynamic Glideslope Scenarios, 36 Dynamic Localizer Scenarios, and 72 Static Error Scenarios, all of which were expected to yield pushes of the "Looks Abnormal" button.

Table 3 tabulates the results for the "Looks Abnormal" button from all data runs. The SV display condition had the poorest results, with more false alarm occurrences (button pushes occurred when none were expected) and more forgotten or missed occurrences (no button pushes occurred when one was expected). The AV display condition had the best results, with fewest false alarm occurrences and no forgotten or missed occurrences.

Table 4 presents more detailed analyses of the false alarm data in terms of the range at which the "Looks Abnormal" button was pushed (mean and standard deviation). If one assumes that it is better to encounter a problem farther from the runway, then the range data reinforces the previous findings, in that the mean range is highest for the AV display condition (and with the smallest standard deviation) and lowest for the SV condition (and with the largest standard deviation), although none of the differences were statistically significant (which is not surprising with the small sample sizes involved).

Table 5 isolates that portion of table 3 that tabulates the results for the "Looks Abnormal" button from the remaining 144 trials in which a button press was expected (the static and dynamic error scenarios). The SV display condition had the poorest results of correctly reported presses and more forgotten or missed occurrences (no button pushes occurred when one was expected). The AV display condition had the best results, with the most correctly reported occurrences and no forgotten or missed occurrences. More detailed analyses of the data will be presented in the Static and Dynamic Error Scenarios analysis section. However, table 6 reapportions the trials of table 5 to the appropriate error scenario. All forgotten or missed presses of the "Looks Abnormal" button occurred on the Static Error Scenario, and most occurred when the SV display condition was in use. None occurred with the AV display condition. The dynamic error scenarios were all detected and reported correctly.

"TOGA" Button Presses

Of the 504 total trials, 360 were expected not to yield any "Looks Abnormal" button pushes, of which 288 were SALs and 72 were incursion scenario trials. Table 7 classifies these data based on whether a "TOGA" was not expected (288 trials) or was expected (72 trials). Very few go-arounds were initiated in those 288 trials in which none were expected, although when they did occur (termed a false alarm), the AV display condition was not in use. Table 8 provides the range and altitude data (means and standard deviations) for those trials in which false go-arounds occurred. With the few sample points available and the large variations involved, no meaningful differences were apparent from these data.

Examination of the 72 incursion trials reveals that few landings were made when a go-around was expected, and none occurred under the AV display condition. Nor were any of the aircraft incursions missed. However, when "TOGAs" were missed (a total of 4 landing attempts with fuel truck incursions), it was usually when the SV display condition was in use. Table 9 provides the range and altitude data (means and standard deviations) for those trials in which "TOGAs" were expected and did occur. The AV display condition yielded correct decisions farther from the runway than the SV condition. (Other differences were not statistically significant.)

Static and Dynamic Error Trials

Of the 144 trials that involved the static and dynamic error scenarios, 36 were Dynamic Glideslope Error Scenarios, 36 were Dynamic Localizer Error Scenarios, and 72 were Static Error Scenarios.

Dynamic Glideslope Error Scenarios

Table 10 shows the tabulated results from the 36 trials of the Dynamic Glideslope Error Scenario and, in particular, for the "Looks Abnormal" button press accuracy, in which a button press was expected for each run. In every instance, regardless of the display condition, the pilots pushed the button appropriately. Two-thirds of the EO display condition runs, under the 700-ft RVR visibility conditions of the scenario, resulted in a go-around (a "TOGA" button press), while one-third (no "TOGA" button press) resulted in successful landing attempts (successful attainment of position near the runway threshold centerline at flare altitude). Forty-two percent of the SV display condition runs resulted in a go-around, while 58 percent resulted in successful landing attempts. All the AV display condition runs resulted in successful landing attempts.

Table 11 presents more detailed analyses of the glideslope error data in terms of the range at which the "Looks Abnormal" button was pushed (mean and standard deviation). With the EO display condition, the pilots acknowledged their recognition of an existing problem earlier than with the SV condition, although none of the differences were statistically significant. With the AV display condition, the system posted an alignment error message at the 9500-ft range, and all pilots used the recalibration capability to remove the effects of the glideslope error and attempted a landing. Table 12 presents the range and altitude data (means and standard deviations) for the "TOGA" button presses. "TOGAs" were initiated earlier with the EO display condition than they were with the SV display condition, although none of the differences were statistically significant.

Dynamic Localizer Error Scenarios

Table 13 tabulates the results from the 36 trials of the Dynamic Localizer Error Scenario, and in particular for the "Looks Abnormal" button press accuracy, in which a button press was expected for each run. In every instance, regardless of the display condition, the pilots pushed the button appropriately. For both the EO and the SV display condition runs, one-half resulted in a go-around (a "TOGA" button press), while the other half (no "TOGA" button press) resulted in successful landing attempts. All AV display condition runs resulted in successful landing attempts.

Table 14 presents more detailed analyses of the localizer error data in terms of the range at which the "Looks Abnormal" button was pushed (mean and standard deviation). With the SV display condition, the pilots acknowledged their recognition of an existing problem earlier than with the EO condition, although the difference was not statistically significant. With the AV display condition, the system posted an alignment error message at the 9500-ft range, and all pilots used the recalibration capability to remove the effects of the localizer error and attempted a landing (the AV mean differences were statistically significant from the other display conditions). Table 15 presents the range and altitude data (means and standard deviations) for the "TOGA" button presses. "TOGAs" were initiated slightly earlier with the EO display condition than with the SV display condition, although the differences were not statistically significant.

Static Error Scenarios

Table 16 shows the tabulated results from the 72 trials of the Static Error Scenario and, in particular, for the "Looks Abnormal" button press accuracy, in which a button press was expected for each run. In every instance of the 24 AV display condition runs, the pilots acknowledged recognition of a problem, elected to recalibrate the INS position information and continued the run, each of which resulted in a successful landing attempt. With the EO display condition, 1 pilot for 1 run did not acknowledge recognition of a problem, but later chose to TOGA at a range of 7859 ft. (This result was interpreted as an error of omission of the button press, rather than as a lack of recognition of the existence of a problem.) In fact, three quarters of the 24 EO runs resulted in TOGA decisions, with only 6 attempts made to land on the sensor image (all attempts were successful in attaining a position near the runway threshold centerline at flare altitude).

With the SV display condition, five different pilots failed to acknowledge recognition of a problem via the "Looks Abnormal" button press during the 24 Static Error Scenario runs. Two of these runs still resulted in "TOGAs," and therefore each was interpreted as an error of omission, rather than as a lack of recognition of the existence of a problem. In the other three runs, the pilots apparently never recognized a problem and actually attempted to land on the erroneously placed synthetic runway (two on the taxiway and one on the parking pad).

In the 19 other runs with the SV display condition, in which the "Looks Abnormal" button presses occurred as anticipated, 12 runs resulted in "TOGAs." The remaining 7 resulted in landing attempts, and 6 were successful. One pilot attempted to land on the erroneously placed synthetic runway (on the parking pad) even though he knew something was wrong. He first acknowledged that a problem existed at a range of 6066 ft.

Table 17 presents more detailed analyses of the static error data in terms of the range at which the "Looks Abnormal" button was pushed (mean and standard deviation). With the EO display condition, the pilots acknowledged their recognition of an existing problem earlier than with the SV condition, although the difference was not statistically significant. With the AV display condition, the system posted an alignment error message at the 9500-ft range, and all pilots used the recalibration capability to remove the effects of the localizer error and attempted a landing (the AV mean differences were statistically significant from the other display conditions). Table 18 presents the range and altitude data (means and standard deviations) for the "TOGA" button presses. "TOGAs" were initiated at essentially the same point with the EO and SV display conditions.

Subjective Results

With a total of 48 questionnaires composed of numerous questions each, only a summary of the subjective results is possible for the purposes of this paper. Such a summary would indicate that from the subjective results, an overwhelming preference for the AV display condition was expressed. As examples, figure 12 presents the results of comparative rank ordering of the display conditions by the pilots for several categories, on a scale from 1 to 10 (1 being the most desirable display and 10 being the least desirable display). The mean ranking is presented, along with the maximum and minimum rankings (not plus or minus the standard deviations). The categories presented compare the display conditions over all scenarios of the experiment and include the effectiveness in reducing pilot workload, the potential for improving safety, and the overall ranking for the entire experiment. In each case, the AV display condition is clearly the preferred concept.

Inferences From Results

The discussion of the inferences from the results of the experiment will consider the individual scenarios first and conclude with an overall treatment.

Dynamic Error Trials

For the pilot to detect a dynamic error condition, in either the dynamic glideslope or localizer error scenario, it was necessary to perceive a conflict between where the flight director was guiding the aircraft and the sensor image of the runway. With the EO display condition, the 700-ft RVR visibility gave no useable information in the out-the-window scene; therefore, reliance upon the sensor image was the only recourse. With the SV display condition, the synthetic scene always agreed with the flight director, and thus a misleading condition was presented. Detection of the dynamic error could only occur through use of the sensor image. With the AV display condition, system advisories based on computerized edge detection routines gave notice of a dynamic error condition when one was present. All pilots chose to use the INS recalibration option to continue the approach.

No meaningful objective data results were extracted from the dynamic error conditions. Earlier or later detections of the conditions, more or fewer go-arounds, and earlier or later initiations of a go-around were not statistically different between the display conditions. However, the pilots' subjective comments indicated that there was complacency inherent with the compelling synthetic scene for the SV display condition, which some of the pilots considered dangerous. Also, that no statistical differences were detected between display conditions indicates that at least these pilots, when flying the SV display condition, were all using the sensor image for these trials early enough and frequently enough to notice the dynamic errors.

Static Error Trials

The most dramatic objective results of the experiment occurred with the static error scenario. Figure 11 illustrates the information available to the pilot to enable detection of the static error for the three display conditions in this scenario. Even with the decision height procedure calls employed during the experiment, which ensured that the pilots displayed the sensor image at least twice during an approach, three landings were inappropriately made with the SV display condition without the pilots apparently being aware of a problem. A fourth inappropriate landing with the SV display was made, even though the pilot had reported being aware of a problem. Subjective comments indicated that the synthetic runway scene was so compelling in this concept that it was easy to ignore the sensor image information.

Incursion Trials

For the runway incursion scenarios (either the taxiing aircraft or the fuel truck), the EO display condition presented both the sensor image and, after range to the incursion had decreased to less than 700 ft, an out-the-window view of the incursion vehicle. With the SV display condition, only the sensor image information was presented. With the AV display, the synthetic scene and the sensor image both included the incursion vehicle, and a system advisory was posted when the range had decreased to appropriate values (less than 2500 ft for the aircraft and less than 1000 ft for the truck). Regardless of the display condition, all aircraft incursions were detected and go-arounds were initiated. However, with the harder-to-detect fuel truck, the SV display condition had three missed incursions and the EO display condition had one missed incursion.

Overall Results

The objective and subjective data results both indicate that with the scenarios employed and the display conditions, as implemented in the study, the SV display condition produced poor and in several cases unsafe performance. They also concur in indicating that the AV display produced superior performance. The safety data, in particular, indicate that similar SVS concepts should not be implemented without incorporating image-processing decision aids for the pilot.

Concluding Remarks

A simulation study was conducted using 12 commercial airline pilots repeatedly flying complex Microwave Landing System (MLS)-type approaches to closely spaced parallel runways. This study compared two synthetic vision sensor insert display concepts and a more conventional electro-optical (EO) display (similar to a Head-Up Display (HUD) with raster capability for sensor imagery) flown under less restrictive visibility conditions and used as a control condition. Various scenarios involving runway traffic incursions (taxiing aircraft and parked fuel trucks) and navigational system position errors (both static and dynamic) were used to assess the pilots' ability to manage the approach task with the display concepts. The two Synthetic Vision Systems (SVS) sensor insert concepts contrasted the simple overlay of sensor imagery on the computer-generated image (CGI) scene without additional image processing (the Synthetic Vision (SV) display) to the complex integration (the Advanced Vision (AV) display) of the CGI scene with pilot-decision aiding using both object and edge detection techniques for detection of obstacle conflicts and runway alignment errors.

The objective and subjective data results both indicate that with the scenarios employed and the display conditions, as implemented in the study, the SV display condition produced poor and in several cases unsafe performance. They also concur in indicating that the AV display produced superior performance. The safety data, in particular, indicate that similar SVS concepts should not be implemented without incorporating image-processing decision aids for the pilot. Subjective comments indicated that the synthetic runway scene was so compelling, as presented in this study, that it was easy to ignore the sensor image information without the decision aid information.

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Table 1. Sensor Insert Experiment Schedule

- Briefing Session (40 min)
- Handling Characteristics Familiarization (20 min)
- Training Session (3 hr)
- Data Collection Session (6 hr)

Table 2. Data Collection Session

Display condition	Scenario[a]	Questionnaires	
		Display evaluation	Display comparisons
EO	R, L, R, RA, L, RS, L, R, LS, LL, L, R, RG, LT	X	
SV	R, L, LT, L, RA, L, LS, R, R, L, RS, LL, R, RG	X	
AV	R, L, R, LS, L, RS, LL, R, RG, L, L, R, RA, LT	X	X

[a]Scenario Conditions:
R signifies a Standard Approach to Landing on runway 8R
L signifies a Standard Approach to Landing on runway 8L
RA signifies the Aircraft Incursion Scenario on runway 8R
LT signifies the Parked Fuel Truck Scenario on runway 8L
RG signifies the Dynamic Glideslope Error Scenario on runway 8R
LL signifies the Dynamic Localizer Error Scenario on runway 8L
RS signifies the Static Error Scenario on runway 8R
LS signifies the Static Error Scenario on runway 8L

Table 3. All "Looks Abnormal" Button Presses

"Looks Abnormal" button (504 trials)	No abnormal expected (360 trials)		Abnormal expected (144 trials)	
	No push	False alarm	Correctly reported	Forgotten or missed
EO (168 trials)	93.3% (112/120)	6.7% (8/120)	97.9% (47/48)	2.1% (1/48)
SV (168 trials)	90.0% (108/120)	10.0% (12/120)	89.6% (43/48)	10.4% (5/48)
AV (168 trials)	98.3% (118/120)	1.7% (2/120)	100.0% (48/48)	0.0% (0/48)

Table 4. Range Data for False Alarm "Looks Abnormal" Button Presses

"Looks Abnormal" button (360 trials)	No abnormal expected		
	False alarm	Range, ft	
		Mean	Standard deviation
EO (120 trials)	6.7% (8/120)	6934.6	2631.3
SV (120 trials)	10.0% (12/120)	5171.9	4801.4
AV (120 trials)	1.7% (2/120)	7395.2	1597.9

Table 5. Expected "Looks Abnormal" Button Presses

"Looks Abnormal" button (144 trials)	Abnormal expected	
	Correctly reported	Forgotten or missed
EO (48 trials)	97.9% (47/48)	2.1% (1/48)
SV (48 trials)	89.6% (43/48)	10.4% (5/48)
AV (48 trials)	100.0% (48/48)	0.0% (0/48)

Table 6. Scenario-Specific Expected "Looks Abnormal" Button Presses

Expected "Looks Abnormal" button (144 trials)	Dynamic glideslope (36 trials)	Dynamic localizer (36 trials)	Static errors (72 trials)	
	Correctly reported	Correctly reported	Correctly reported	Forgotten or missed
EO (48 trials)	100.0% (12/12)	100.0% (12/12)	95.8% (23/24)	4.2% (1/24)
SV (48 trials)	100.0% (12/12)	100.0% (12/12)	79.2% (19/24)	20.8% (5/24)
AV (48 trials)	100.0% (12/12)	100.0% (12/12)	100.0% (24/24)	0.0% (0/24)

Table 7. All "TOGA" Button Presses

"TOGA" button (360 trials)	No TOGA expected (288 trials)		TOGA expected (72 trials)	
	No TOGA	False TOGA	Correct TOGA	Missed TOGA
EO (120 trials)	97.9% (94/96)	2.1% (2/96)	95.8% (23/24)	4.2% (1/24)
SV (120 trials)	96.9% (93/96)	3.1% (3/96)	87.5% (21/24)	12.5% (3/24)
AV (120 trials)	100.0% (96/96)	0.0% (0/96)	100.0% (24/24)	0.0% (0/24)

Table 8. Range and Altitude Data for No TOGA-Expected Scenarios

"TOGA" button (288 trials)	No TOGA expected (288 trials)				
	False TOGA	Range, ft		Altitude, ft	
		Mean	Standard deviation	Mean	Standard deviation
EO (96 trials)	2.1% (2/96)	3381.6	2164.2	157.8	118.5
SV (96 trials)	3.1% (3/96)	3872.4	3045.0	189.5	158.4
AV (96 trials)	0.0% (0/96)				

Table 9. Range and Altitude Data for TOGA-Expected Scenarios

"TOGA" button (72 trials)	TOGA expected (72 trials)				
	Correct TOGA	Range, ft		Altitude, ft	
		Mean	Standard deviation	Mean	Standard deviation
EO (24 trials)	95.8% (23/24)	1744.4	657.3	75.1	31.4
SV (24 trials)	87.5% (21/24)	1565.6	504.6	65.6	21.6
AV (24 trials)	100.0% (24/24)	2143.6	471.8	93.3	22.9

Table 10. Dynamic Glideslope Error Scenario Results

Dynamic glideslope error (36 trials)	"Looks Abnormal"	TOGA	Successful landing attempt
EO (12 trials)	100.0% (12/12)	66.7% (8/12)	33.3% (4/12)
SV (12 trials)	100.0% (12/12)	41.7% (5/12)	58.3% (7/12)
AV (12 trials)	100.0% (12/12)	0.0% (0/12)	100.0% (12/12)

Table 11. Range Data for "Looks Abnormal" Presses Within Dynamic Glideslope Error Scenarios

Dynamic glideslope error (36 trials)	"Looks Abnormal" presses	Range, ft	
		Mean	Standard deviation
EO (12 trials)	100.0% (12/12)	8670.0	705.6
SV (12 trials)	100.0% (12/12)	8351.3	1067.2
AV (12 trials)	100.0% (12/12)	9069.9	559.9

Table 12. Range and Altitude Data for "TOGA" Presses Within Dynamic Glideslope Error Scenarios

Dynamic glideslope error (36 trials)	Chose to TOGA	Range, ft		Altitude, ft	
		Mean	Standard deviation	Mean	Standard deviation
EO (12 trials)	66.7% (8/12)	6951.9	1193.3	265.1	110.5
SV (12 trials)	41.7% (5/12)	5565.9	1124.6	138.7	77.0
AV (12 trials)	0.0% (0/12)				

Table 13. Dynamic Localizer Error Scenario Results

Dynamic localizer error (36 trials)	"Looks Abnormal"	TOGA	Successful landing attempt
EO (12 trials)	100.0% (12/12)	50.0% (6/12)	50.0% (6/12)
SV (12 trials)	100.0% (12/12)	50.0% (6/12)	50.0% (6/12)
AV (12 trials)	100.0% (12/12)	0.0% (0/12)	100.0% (12/12)

Table 14. Range Data for "Looks Abnormal" Presses Within Dynamic Localizer Error Scenarios

Dynamic localizer error (36 trials)	"Looks Abnormal" presses	Range, ft	
		Mean	Standard deviation
EO (12 trials)	100.0% (12/12)	5900.0	1467.6
SV (12 trials)	100.0% (12/12)	6325.4	1567.0
AV (12 trials)	100.0% (12/12)	8270.5	628.7

Table 15. Range and Altitude Data for "TOGA" Presses Within Dynamic Localizer Error Scenarios

Dynamic localizer error (36 trials)	Chose to TOGA	Range, ft		Altitude, ft	
		Mean	Standard deviation	Mean	Standard deviation
EO (12 trials)	50.0% (6/12)	4219.6	2187.2	204.3	115.2
SV (12 trials)	50.0% (6/12)	4125.4	704.8	201.2	36.2
AV (12 trials)	0.0% (0/12)				

Table 16. Static Error Scenario Results

Static error (72 trials)	"Looks Abnormal"	Chose to TOGA	Successful landing attempt	Unsuccessful landing attempt
EO (24 trials)	95.8% (23/24)	75.0% (18/24)	25.0% (6/24)	0.0% (0/24)
SV (24 trials)	79.2% (19/24)	58.3% (14/24)	25.0% (6/24)	16.7% (4/24)
AV (24 trials)	100.0% (24/24)	0.0% (0/24)	100.0% (24/24)	0.0% (0/24)

Table 17. Range Data for "Looks Abnormal" Presses Within Static Error Scenarios

Static error (72 trials)	"Looks Abnormal" presses	Range, ft	
		Mean	Standard deviation
EO (24 trials)	95.8% (23/24)	6933.8	1707.7
SV (24 trials)	79.2% (19/24)	6735.0	1695.1
AV (24 trials)	100.0% (24/24)	7670.0	677.5

Table 18. Range and Altitude Data for "TOGA" Presses Within Static Error Scenarios

Static error (72 trials)	Chose to TOGA	Range, ft		Altitude, ft	
		Mean	Standard deviation	Mean	Standard deviation
EO (24 trials)	75.0% (18/24)	3990.3	1875.8	193.2	95.7
SV (24 trials)	58.3% (14/24)	3958.5	2753.5	195.9	138.8
AV (24 trials)	0.0% (0/24)				

Figure 1. The Visual Imaging Simulator for Transport Aircraft Systems.

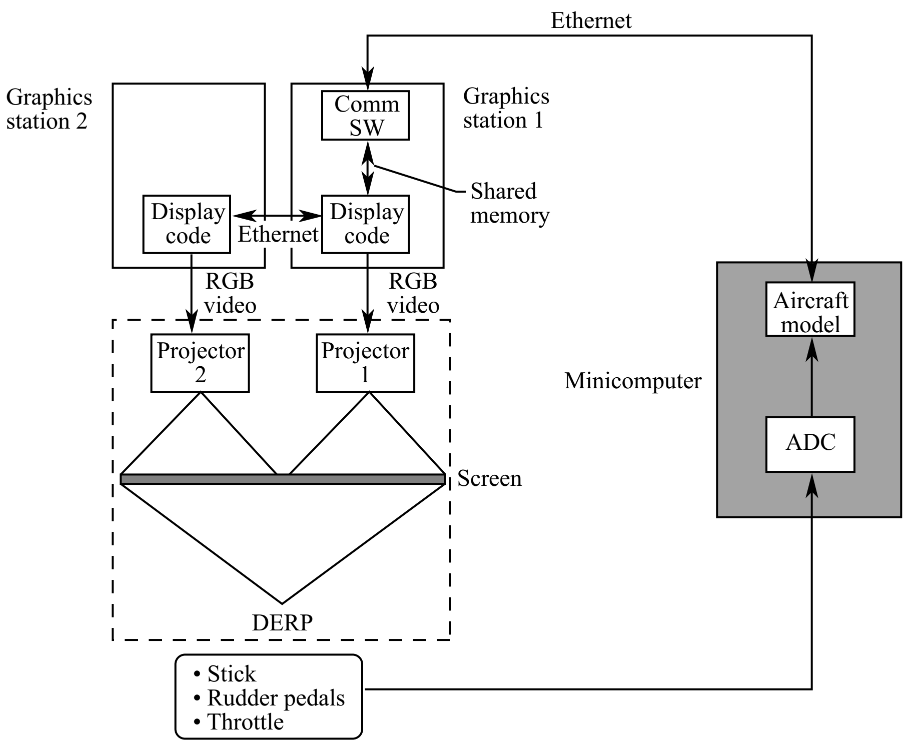
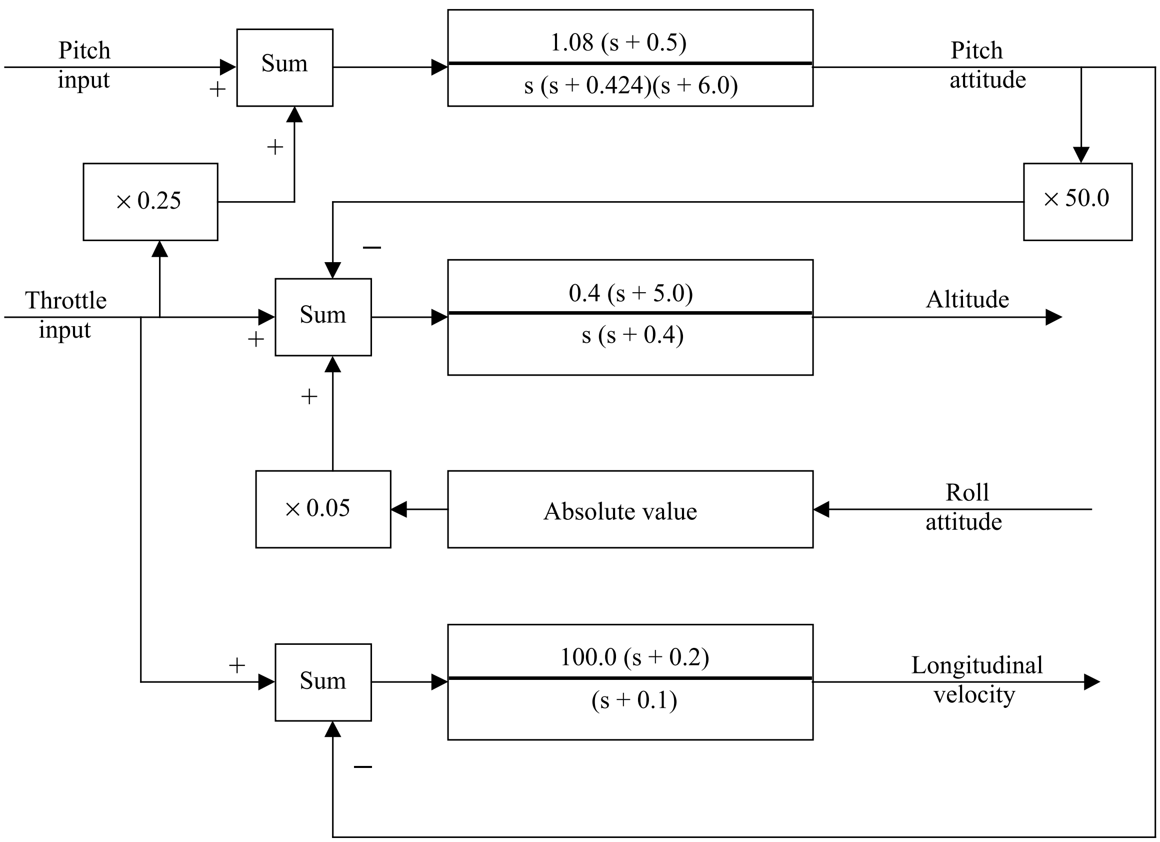
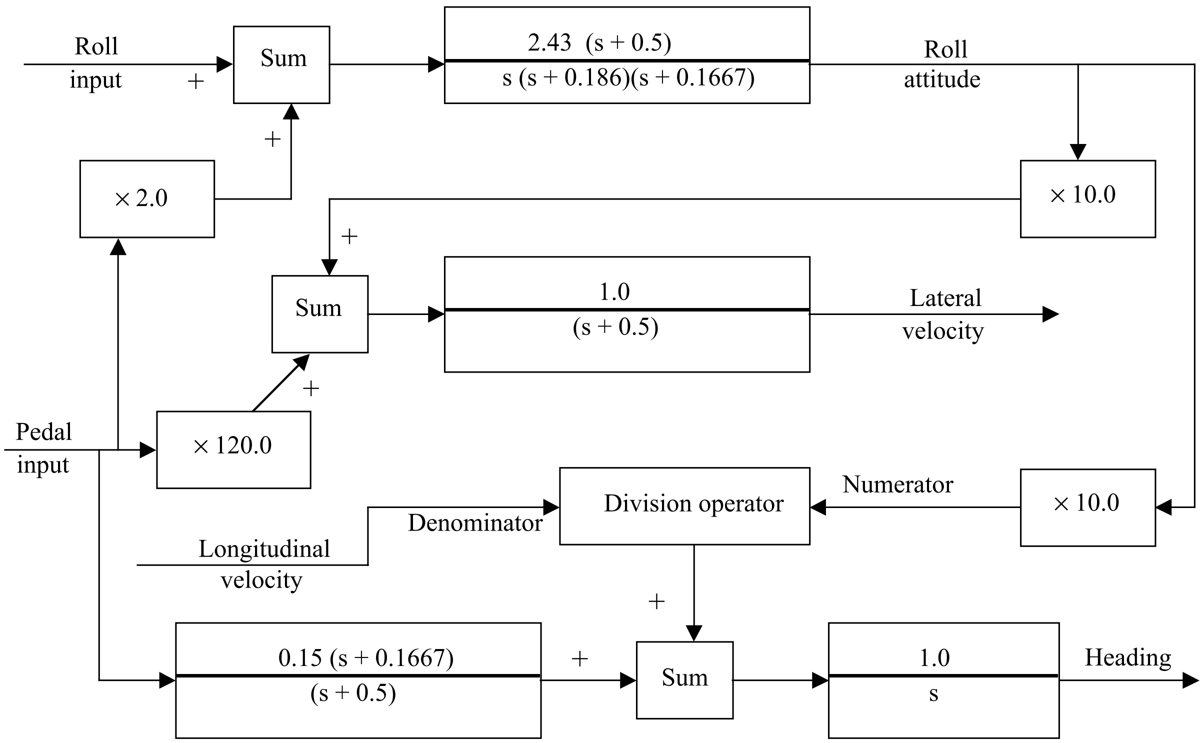


Figure 2. Arrangement of the VISTAS dual projection system.



(a) Longitudinal degrees of freedom.

Figure 3. Block diagram of simplified six-degree-of-freedom aircraft model using LaPlace(s) operators.



(b) Lateral degrees of freedom.

Figure 3. Concluded.

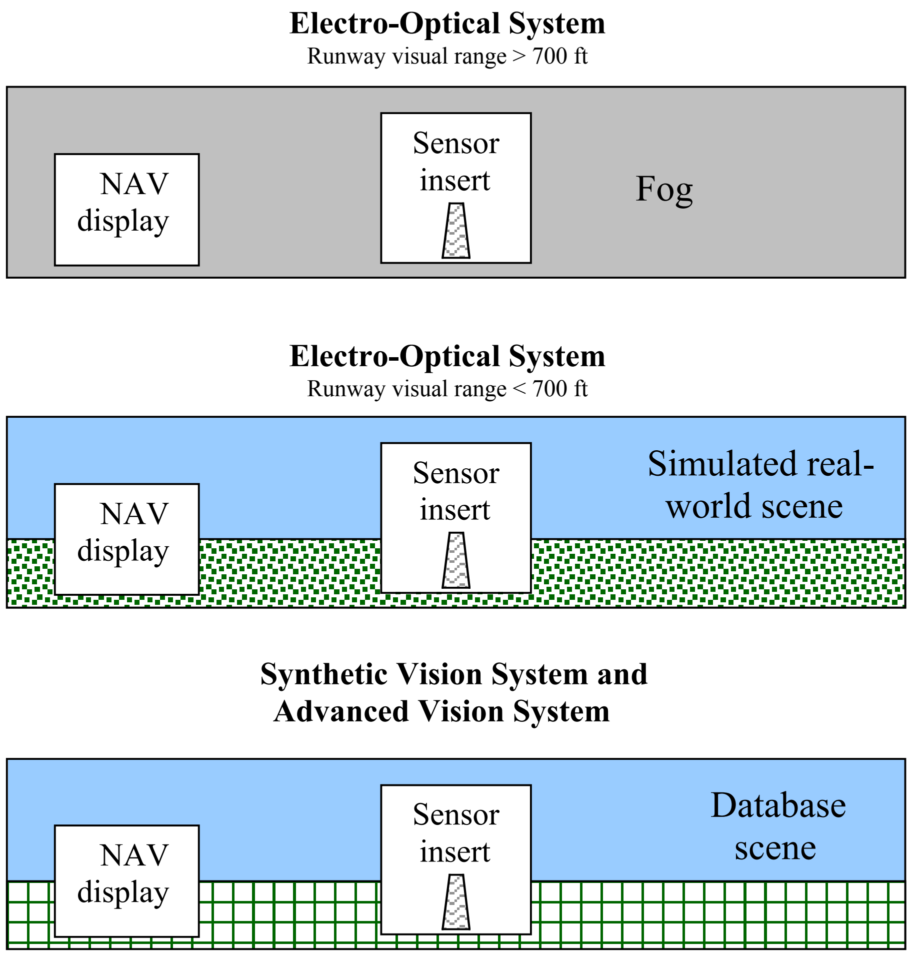


Figure 4. Representation of display conditions.

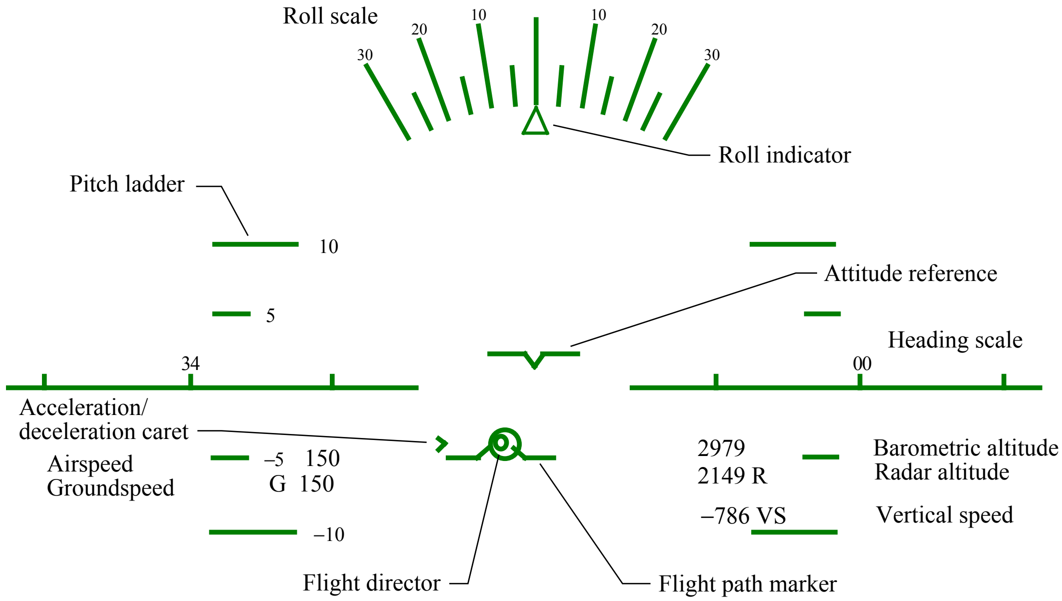


Figure 5. Symbology set.

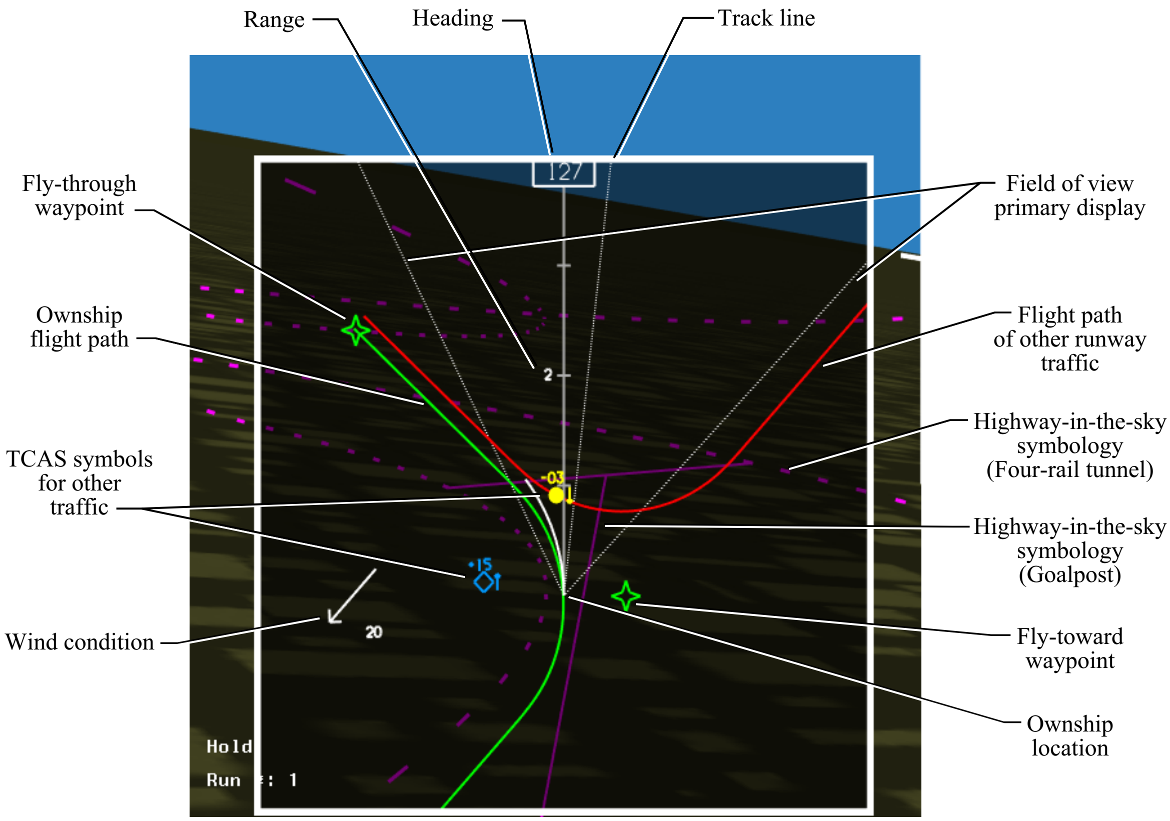


Figure 6. Navigation Display overlaid on outside scene.

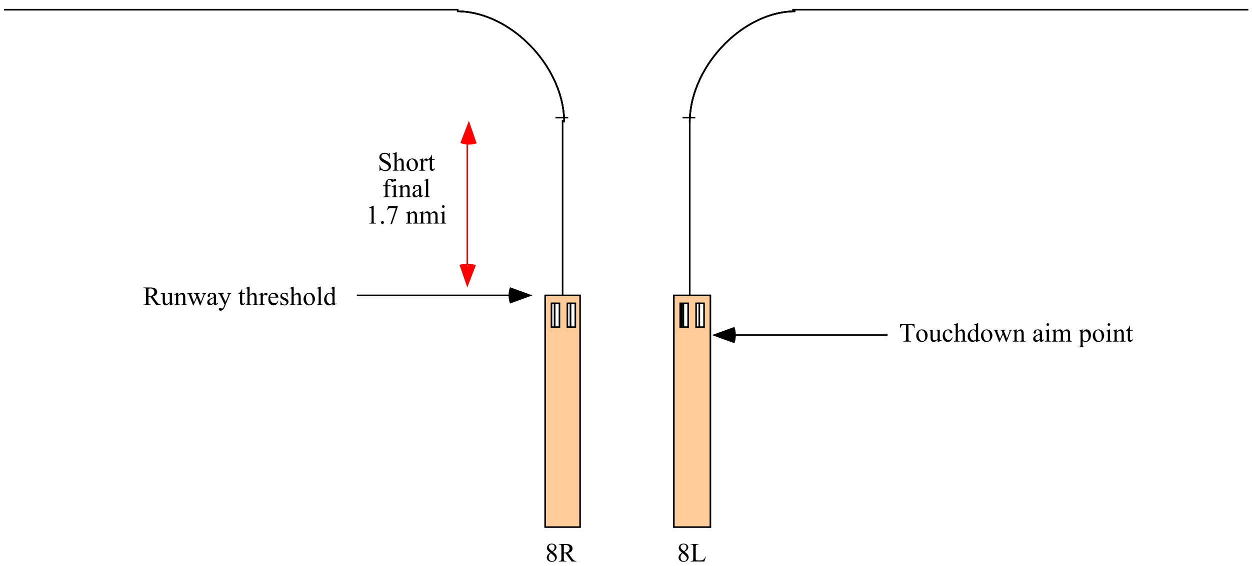


Figure 7. The Standard Approach to Landing paths for runways 8L and 8R (3° glideslope).

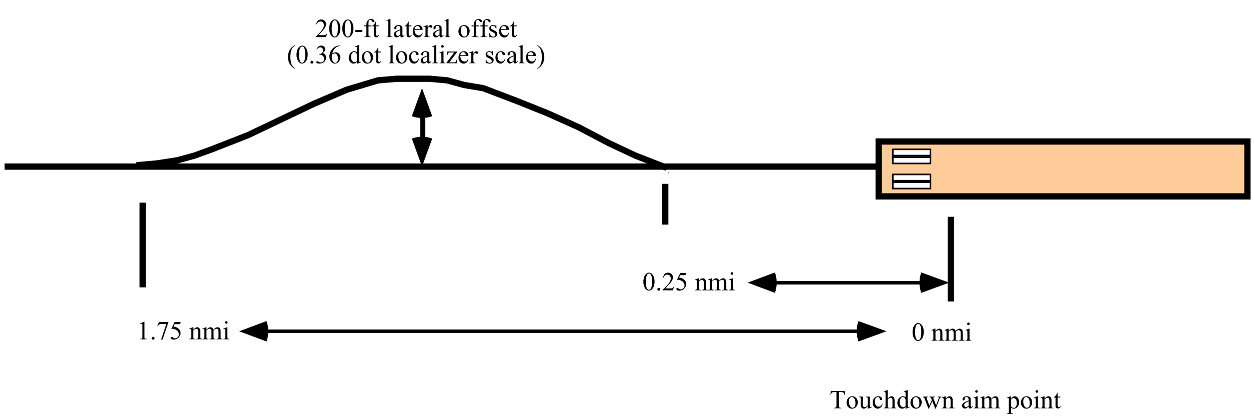


Figure 8. Lateral flight path imposed by Dynamic Localizer Error Scenario.

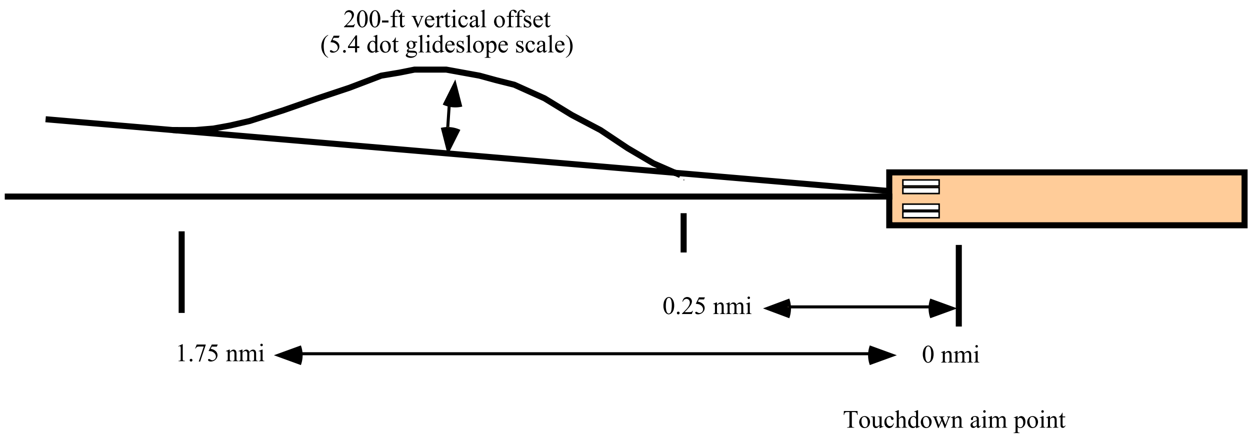


Figure 9. Vertical flight path imposed by Dynamic Glideslope Error Scenario.

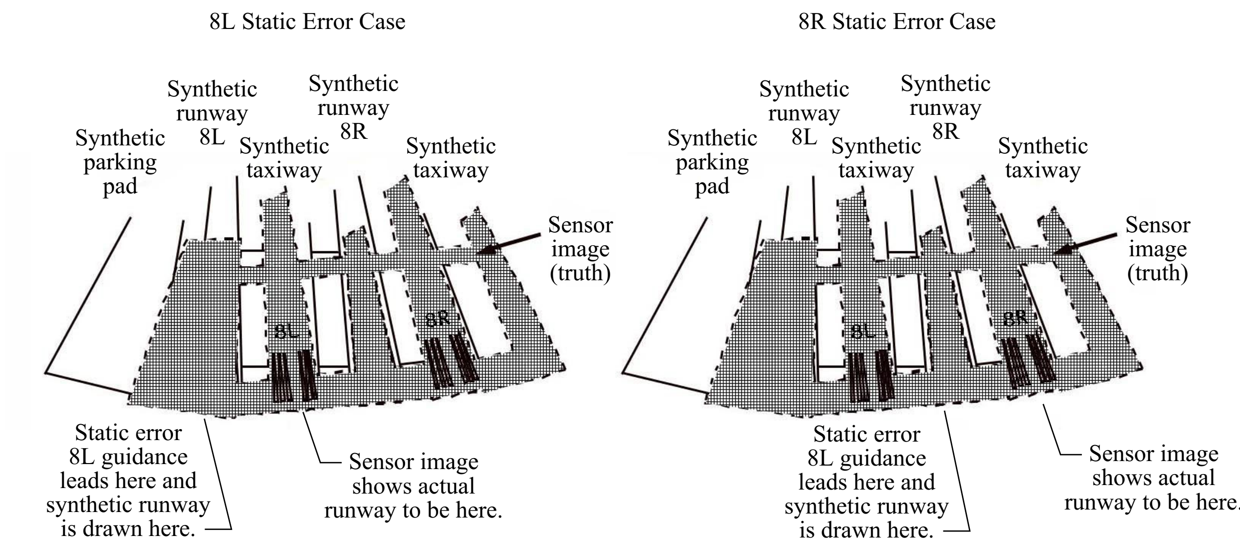


Figure 10. Implied locations of active runway imposed by the two cases of the Static Error Scenario.

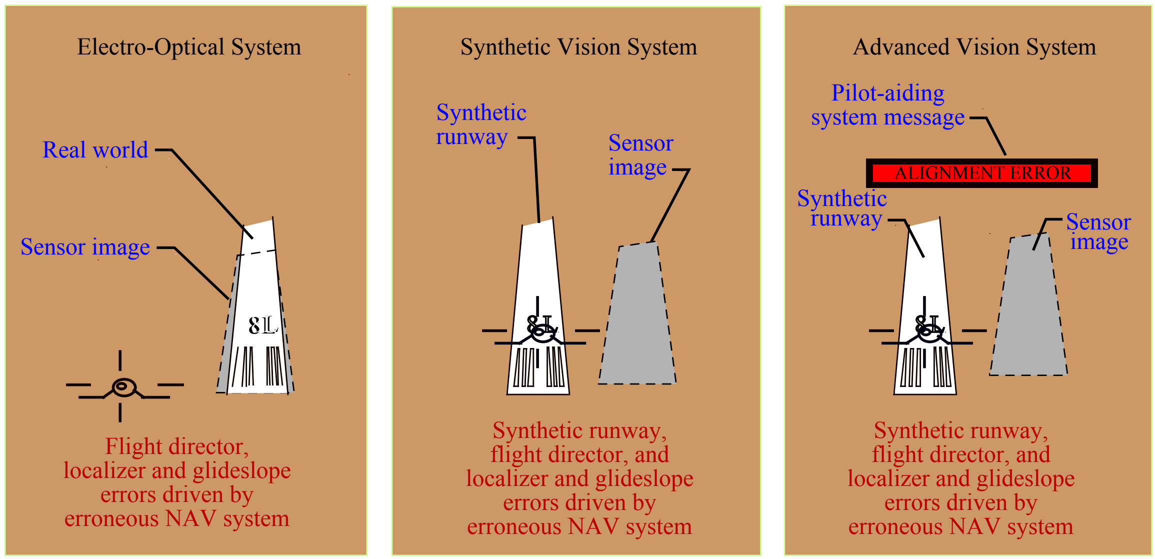


Figure 11. Illustration of appearance of three display conditions for one of the two Static Error Scenarios.

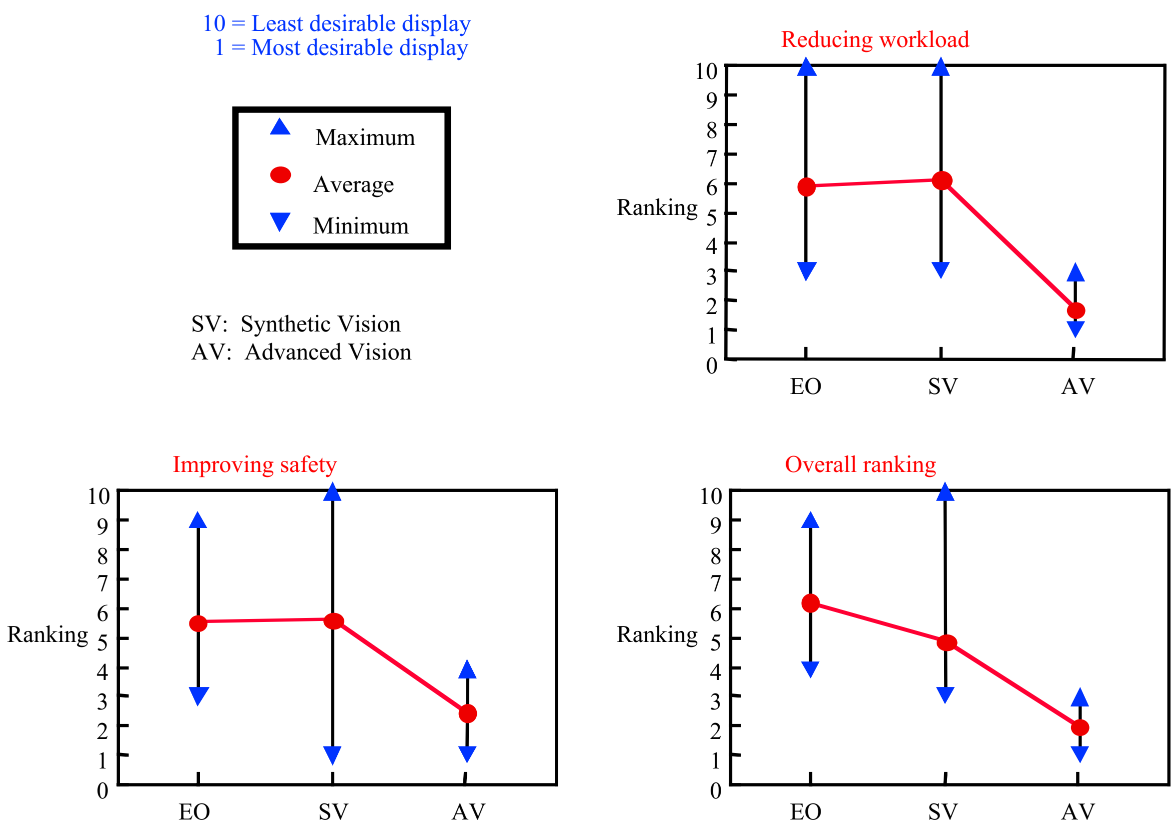


Figure 12. Summary of subjective rank ordering comparisons of display conditions.

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14. ABSTRACT
A simulation study was conducted in 1994 at Langley Research Center that used 12 commercial airline pilots repeatedly flying complex Microwave Landing System (MLS)-type approaches to parallel runways under Category IIIc weather conditions. Two sensor insert concepts of "Synthetic Vision Systems" (SVS) were used in the simulated flights, with a more conventional electro-optical display (similar to a Head-Up Display with raster capability for sensor imagery), flown under less restrictive visibility conditions, used as a control condition. The SVS concepts combined the sensor imagery with a computer-generated image (CGI) of an out-the-window scene based on an onboard airport database. Various scenarios involving runway traffic incursions (taxiing aircraft and parked fuel trucks) and navigational system position errors (both static and dynamic) were used to assess the pilots' ability to manage the approach task with the display concepts. The two SVS sensor insert concepts contrasted the simple overlay of sensor imagery on the CGI scene without additional image processing (the SV display) to the complex integration (the AV display) of the CGI scene with pilot-decision aiding using both object and edge detection techniques for detection of obstacle conflicts and runway alignment errors.

15. SUBJECT TERMS
Pictorial displays; Weather-penetrating sensors; Runway traffic incursions; Synthetic Vision; Enhanced Vision

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