

FLIGHT TEST EVALUATION OF SITUATION AWARENESS BENEFITS OF INTEGRATED SYNTHETIC VISION SYSTEM TECHNOLOGY FOR COMMERCIAL AIRCRAFT

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Research was conducted onboard a Gulfstream G-V aircraft to evaluate integrated Synthetic Vision System concepts during flight tests over a 6-week period at the Wallops Flight Facility and Reno/Tahoe International Airport. The NASA Synthetic Vision System incorporates database integrity monitoring, runway incursion prevention alerting, surface maps, enhanced vision sensors, and advanced pathway guidance and synthetic terrain presentation. The paper details the goals and objectives of the flight test with a focus on the situation awareness benefits of integrating synthetic vision system enabling technologies for commercial aircraft.

Introduction

A “synthetic vision system” is an electronic means of displaying the pertinent and critical features of the environment external to the aircraft through a computer-generated image of the external scene topography using on-board databases (e.g., terrain, obstacles, cultural features), precise positioning information, and flight display symbologies that may be combined with information derived from a weather-penetrating sensor (e.g., runway edge detection, object detection algorithms) or with actual imagery from enhanced vision sensors.

NASA Synthetic Vision System Project

NASA’s Synthetic Vision Systems (SVS) project is developing technologies with practical applications that will eliminate low visibility conditions as a causal factor to civil aircraft accidents while replicating the operational benefits of clear day flight operations, regardless of the actual outside visibility condition. A major thrust of the SVS project involves the development/demonstration of affordable, certifiable display configurations that provide intuitive out-the-window terrain and obstacle information with advanced pathway guidance. The SVS concept being developed at NASA encompasses the integration of tactical and strategic Synthetic Vision Display Concepts (SVDC) with Runway Incursion Prevention System (RIPS) alerting, real-time terrain database integrity monitoring equipment (DIME), and Synthetic Vision Sensors (SV-Sensors), using an enhanced weather radar for real-time object detection, runway confirmation, and database integrity monitoring.

Previous flight tests (Glabb et al., 2003; Kramer et al., 2004) of SVS have primarily focused on the general use and utility of SVS for providing flight critical guidance and improved terrain/situation awareness. The research objectives of these previous

flight tests also focused on SVS implementation issues, such as display requirements (e.g., size, content, and format) and on the development of SVS enabling technologies (e.g., RIPS, EVS, and DIME).

While research to date has proven that precision navigation and on-board databases can provide the primary framework for substantial improvements in terrain/situation awareness with SVS, independent integrity monitors are envisioned as an integral component of SVS to meet flight-critical safety requirements. This functionality is being developed by NASA and others to utilize existing on-board sensors (e.g., weather radars, high quality radar altimeters) to facilitate implementation. Specific on-board integrity functions include independent air-to-air, air-to-ground, ground-to-ground, and ground-to-air traffic and object/obstacle detection and surveillance, a runway incursion monitoring, and database integrity and registration (navigational position confirmation via terrain feature extraction). Additionally, SVS concepts are being developed to augment and complement the independent capabilities of weather-penetrating, enhanced vision imaging sensors during low visibility landing and surface operations conditions. These technologies form the basis for monitoring the dynamic flight environment and thereby supplementing the synthetic world with real-time, direct measurement of the surrounding terrain and air/ground traffic for flight-critical applications.

SVS Integrated Flight Test

A flight test evaluation was jointly conducted (in July and August 2004) by NASA Langley Research Center and Gulfstream Aerospace Corporation under NASA’s Aviation Safety and Security (AvSSP), Synthetic Vision System program. A Gulfstream G-V aircraft was flown over a 3-week period in the Reno/Tahoe International Airport (RNO) local area and an additional 3-week period in the Wallops

Flight Facility (WAL) local area to evaluate an integrated Synthetic Vision System concept, including real-time, integrity monitoring functions.

Flight Test Objectives

The primary G-V Synthetic vision Integrated Technology Evaluation (GVSITE) flight test objective was to evaluate the utility and acceptance of an integrated Synthetic Vision *System* intended for commercial and business aircraft in a terrain-challenged operational environment.

The integrated SV system included computer-generated terrain presented on Primary Flight Displays (PFD) and Electronic Attitude and Direction Indicators in place of the conventional blue sky and brown ground; monochrome textured terrain presented on Head-Up Displays (HUD); plan view or perspective views of computer-generated terrain and obstacles on Navigation Displays (ND); and datalink, sensors, and algorithms to provide and verify required information for display. In addition, symbology and algorithms designed as integrity monitors and detection/surveillance monitors to enhance pilot situational awareness during surface and landing phase operations, and prevent or alert to potential runway incursions, was also part of the SV system tested during the GVSITE flight test.

Method

Pilot Participants

Ten evaluation pilots (EPs), representing the airlines, a major transport aircraft manufacturer, the Federal Aviation Administration, and the Joint Aviation Authority, flew research flights totaling approximately 45 flight test hours. One hundred and forty-five flight test runs were conducted to evaluate the NASA SVS concepts at WAL (8 pilots) and RNO airports (7 pilots). Five of the ten EPs flew at both test locations. All participants were HUD qualified.

Test Aircraft

The flight test was conducted using a Gulfstream G-V aircraft. The left seat of the G-V was occupied by the EP and the right seat was occupied by a Gulfstream Safety Pilot (SP). The left seat included in the installation of two 8"x8" (approximately 768x768 pixel resolution) head-down displays for evaluation of the PFD and ND concepts (Figure 1), an overhead Rockwell-Collins HGS-3300 HUD for evaluation of head-up concepts, and a voice recognition and speech (VRS) system for the pilot-vehicle interface to the SV displays. A vision restriction device (VRD) was placed in the left-seat forward windscreen to block the EP's forward vision and thus simulate Instrument

Meteorological Conditions (IMC) when needed experimentally. The VRD was removed no lower than 200 ft. above field elevation.



Figure 1. GulfStream-V SVS Head-Down Displays

Runway Incursion Prevention System

Real-time, RIPS algorithms (from NASA/LaRC in-house developments and the Rannoch Corporation) and RIPS display concepts were integrated into the Synthetic Vision Display Concepts for GVSITE. RIPS receives data on potential airborne and surface intruders through datalink and onboard sensors, processes the data through RIPS algorithms and known aircraft position to detect potential hazards, and interfaces through cockpit displays and communication systems to warn the crew. Only the NASA LaRC algorithms results are discussed in the paper.

SV Sensors

A modified WxR-2100 multi-mode weather radar with mounting trays, waveguide with a matched load termination, wiring harness, control head, pedestal, and antenna was installed in the G-V to support SV-Sensor research objectives. During the flight test, the radar operated in one of four modes: (a) weather radar – standard weather radar functionality; (b) runway outline identification – ground clutter returns were analyzed with aircraft navigational state data to provide an estimate runway position; (c) terrain feature extraction - ground clutter returns were provided to the DIME as source data, (d) air-to-ground obstacle detection – radar data processing was used in an attempt to identify objects and obstacles on the active runway while on approach.

Database Integrity Monitoring Equipment

A real-time digital terrain elevation data (DTED) integrity monitoring capability was designed to detect statistically significant differences between sensed terrain data and the stored DTED through two DIME concepts:

1. Using inputs from the ship's standard radar altimeter and an internal GPS Wide Area Augmentation System (WAAS) receiver, an estimate of DTED integrity was generated in real-time. This DIME-provided integrity measure was used to create a loss-of-integrity alert which was part of the Synthetic Vision Display concepts. This integrity alert function was experimentally tested.
2. A forward-looking monitor was also tested that makes use of WxR2100 and inertial reference unit (IRU) measurements to complement the radar altimeter-based integrity monitor.

An experimental GPS bi-static radar equipment was also installed in the DIME rack to collect data to support subsequent algorithm development for a possible third database integrity method.

Enhanced Vision Sensor

Enhanced Vision System (EVS) capability was provided by the standard G-V Kollsman Forward Looking InfraRed (FLIR) camera. The cryogenically-cooled FLIR camera operates in the low-to-mid IR wavelengths using a sensor with approximately 320 Horizontal x 240 Vertical pixel resolution. The EVS generated an RS-170 video signal which was up-converted to an RS-343 video signal for the Flight Dynamics HUD through a Folsom scan converter.

Experimental Display Conditions

Four display conditions (Figure 3) were evaluated while EPs performed approaches and departures at RNO and WAL airports:

1. The first display condition (Baseline) utilized both the head-down and head-up research displays. The head-down displays represented a conventional PFD and ND. The ND was a coplanar display with a map-centered Terrain Awareness and Warning System (TAWS) display and a vertical situation display (VSD). No synthetic terrain information was presented on either the head-up or head-down displays in the Baseline condition.
2. The second display condition (Baseline FLIR) had the same head-down PFD and ND concepts as the Baseline display condition, but it included FLIR on the raster channel of the HUD.
3. The third display condition (Advanced SVS) utilized the head-down displays and the HUD. In addition to the conventional flight symbology typically found on a PFD and HUD, these displays also included advanced pathway guidance and terrain information using a

combination of photo-realistic and elevation-based shading texturing. The ND had terrain information in addition to the TAWS warning and caution overlays and VSD. A surface guidance map display was presented on the navigation display for scenarios with surface operations. The surface map showed the ATC taxi route and active runways and provided alerting of non-normal events (e.g., cross hold-line of active runway, off-route)

4. The fourth display condition (Advanced SVS – No HUD) was exactly the same as the Advanced SVS display condition but it did not employ the HUD. Hence, the EPs primary flight reference was solely head-down.

Flight Evaluation Tasks

At each flight test location (WAL, RNO), EPs flew multiple scenarios which included: approach with wave-off to a departure; approach and landing; taxi operations; low-speed rejected take-off; and takeoff and departure. In addition to nominal approach and departure tasks, there were non-normal runs flown with each display condition which included runway incursion (RI) scenarios and database integrity monitoring scenarios. The RI scenarios included potential incursions with either a Beech King Air (Be-200) or a specially-equipped recreational vehicle during approach, surface, and departure operations. These scenarios were pre-briefed and carefully staged to ensure safety of flight and maximize masking of the RI scenario from the EP. The database integrity monitoring scenarios purposefully introduced a SV database offset either laterally or vertically with the real world. The pathway guidance was always correct and the EPs were instructed to fly with respect to the guidance and not the database image. The EPs were instructed to fly each approach as precisely as possible using the display information available to them, as the effect of the display information on the EPs ability to fly the approaches would be quantitatively and qualitatively evaluated. In addition, the EPs were instructed to taxi as close as possible to the centerline of the taxiway, using a ground speed between 15 and 20 knots with a target speed of 18 knots.

Runway Incursion Scenarios

There were seven runway incursion scenarios used for evaluation of RIPS alerting and surface map displays. The scenarios were:

1. Crossing Runway – Departure of test aircraft and departure of incursion aircraft (WAL, RNO)
2. Crossing Runway – Departure of test aircraft and arrival of incursion aircraft (WAL)

3. Crossing Runway – Arrival of test aircraft and departure of incursion aircraft (WAL, RNO)
4. Crossing Runway – Arrival of test aircraft and arrival of incursion aircraft (WAL)
5. Taxi crossing/departure – Taxi across hold line of test aircraft during departure of incursion aircraft on active runway (WAL, RNO)
6. Take-Off Hold/Arrival --- Incursion aircraft on short final and test aircraft at take-off position (WAL)
7. Arrival/Take-Off Hold --- Test aircraft on short final and incursion aircraft at take-off position (WAL, RNO)

Results

Approach Phase, Flight Technical Error

The independent variables were display type (Baseline, Baseline FLIR, Advanced SVS, Advanced SVS-No HUD), path type (Sparks East 16R, Sparks North 16R, South Hills East 34L, and South Hills South 34L), and pilot. The dependent measures were RMS lateral path error and RMS vertical path error. The calculation for RMS path error began on each run when the pilot entered the tunnel the first time. Display type, path type, pilot, and the second order interactions between the main factors were not significant ($p > .05$) for either measure. The pilot performance results are not surprising and are supported by past research (Kramer et al., 2004, Prinzel et al., 2004). Each display concept utilized the same pursuit guidance control laws and symbology (i.e., the flight path marker, integrated single cue guidance symbol and path deviation indicators which commanded the pilot where to fly). The addition of the tunnel concepts in the advanced display formats were not significant in this quantitative path performance data, but did, as shown in the following, influence the subjective workload and SA measures. The FTE results also do not neatly include the influence guidance and tunnel symbology with off-path starting conditions, because it was not possible to precisely control the run-start conditions in the dynamic air traffic/flight test environment; thus, the FTE results were normalized by using the tunnel intercept condition (whether the tunnel was explicitly shown or not) to begin the FTE “scoring.”

Approach Phase, Mental Workload

There were no statistically significant differences for the Air Force Revised Workload Estimation Scale amongst the display concepts, ($p > .05$). Pilots rated the workload from “light” (Advanced SVS) to “moderate activity” (Baseline). However, SWORD ratings during approach revealed that pilots rated the baseline condition significantly higher in mental

workload than the other three display conditions ($F(3,33) = 8.470$, $p < .05$). The baseline condition is the only display configuration that doesn’t explicitly have terrain information on the PFD or HUD.

Approach Phase, Pilot Situation Awareness

The SA-SWORD analysis revealed two unique subsets for display concept comparisons for situation awareness during approach ($F(3,27) = 8.188$, $p < .05$): (1) advanced SVS (highest) and (2) advanced SVS – no HUD, Baseline with FLIR, and Baseline (lowest). The advanced configuration differs from the other three configurations, principally by having terrain information on the PFD and HUD.

Surface Operations, Workload

For surface operations, there were three unique subsets for SWORD ratings ($F(3,30) = 23.196$, $p < .05$): (a) Advanced SVS (lowest), (2) Advanced SVS – no HUD, and (3) Baseline with FLIR and Baseline (highest). Two prominent display configuration differences influence the surface operations results – the presence of the Electronic Moving Map (EMM) in the advanced display concept and surface guidance symbology and the presence of a HUD.

Surface Operations, Situation Awareness

There was also a significant effect found for SA-SWORD for surface operations ($F(3,33) = 14.075$, $p < .05$) revealing three unique subsets for display concept comparisons for situation awareness for surface operations: (1) advanced SVS (highest); (2) Advanced SVS – no HUD and Baseline with FLIR; and (3) Baseline with FLIR and Baseline (lowest). The situation awareness results mirror those of the workload results, signifying the importance of advanced guidance and situation information on a HUD for ground operations. The importance of situation information is further highlighted by pilot subjective reports of improved SA for ground operations using the EMM as highlighted in the following.

Pilots rated their situation awareness very high for surface operations when using the surface map displays, considered an essential part of the integrated NASA synthetic vision system, compared to surface operations using the baseline displays. Post-experiment questions were asked of pilots regarding surface operations and situation awareness using the surface map display and alerting. For each question, pilots rated 1 (completely disagree) to 7 (completely agree) on a Likert scale in terms of agreement for the following questions (Figure 2):

Q1: Where am I? “The display concept provides

sufficient awareness of my ownship position with respect to runways, taxiways, and stationary objects.”

Q2: Where am I relative to Other Moving Objects?“

The display concept provides sufficient awareness of my ownship position with respect to moving traffic, such as vehicles and other aircraft.”

Q3: What is the status of surfaces in the movement area? “The display concept provides sufficient awareness of the status of taxi and runway surfaces.”

Q4: Where am I relative to my route/destination?

“The display concept provides sufficient awareness of my cleared route.”

Q5: What control inputs should I make to maintain my cleared route? “The display concept provides sufficient guidance cues needed to follow my cleared route.”

Figure 2 graphically demonstrates that pilots rated the EMM display significantly higher for situation awareness across all five questions that addressed a different facet of SA. On average, pilots completely agreed with the statements that the EMM significantly enhanced awareness of ownship position and those of other aircraft and vehicles, cleared taxi route, and active runways and surface information. Pilot unanimously considered the EMM to be an essential and needed cockpit display that would substantially enhance aviation safety and efficiency.

Runway Incursion Prevention

Pilots encountered seven runway incursion scenarios at WAL and 4 incursion scenarios at RNO. A total of 82 experimental runs were conducted at WAL and 60 runs were conducted at RNO. Overall, the RIPS algorithm results are very promising (data analysis is on-going), showing successful detection and minimal false alarms (Jones, in press).

In terms of the situation awareness provided by RIPS, pilots rated the RIPS alerting to be better than the baseline conditions for “likelihood of detecting and preventing a runway incursion.” The inclusion of RIPS alerting was rated 6.96/7.0 (very high likelihood) compared to only 2.64/7.0 (low likelihood) for the baseline conditions. 9/10 pilots reported that the incursion alerts were provided in a timely manner and felt that RIPS significantly enhanced RI safety compared to current technology and procedures (cockpit, ground, ATC). After familiarization, the majority of the pilots (9/10) trusted the alerting and initiated a go-around or evasive action on the ground to avoid a runway incursion. Only one pilot needed to first confirm the hazard before initiating a go-around.

Integrity Monitoring

Pilots were asked to provide two ratings, one on the effectiveness and one on the essentialness, on the presentation of NOTAM alerts (e.g., NOTAM tower, closed rwy) and DIME alerts for a synthetic vision system. Pilots used a Likert rating scale (1-7) to rate the effectiveness and essentialness of the NOTAM and DIME information presentations. An average rating of 4.2 (moderately effective/essential) was reported for NOTAM tower alerts but pilots rated NOTAM closed rwy alert presentation to be completely effective and essential (7.0). For DIME alerts, pilots rated the information presentation as being highly effective (6.42) and completely essential (7.0).

Pilot Preference

Pilots were asked to rank order display concepts in terms of (a) pilot performance and flight path awareness and (b) pilot preference for IMC approaches. A Friedman test ($p < .05$) evinced a significant ranking for both questions in the order of: (1) advanced SVS (highest); (2) Advanced SVS – no HUD; (3) Baseline with FLIR; and (4) Baseline lowest). Pilots also provided a number of useful comments that have been used to guide subsequent and future SVS developments. Overall, however, pilots unanimously applauded the safety and situation awareness benefits of the NASA integrated synthetic vision system.

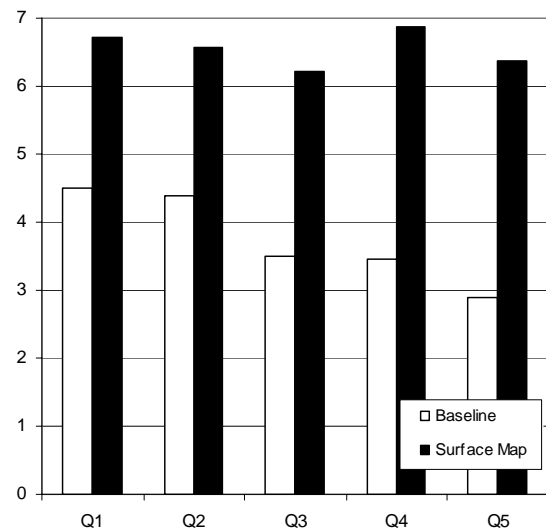


Figure 2. Situation awareness for surface operations

Conclusions

The flight test marked the first time NASA’s technologies have been integrated as a complete system incorporating synthetic terrain primary flight and navigation displays, advanced weather radar

object detection, synthetic vision database integrity monitoring, refined dynamic tunnel and guidance concepts, surface map displays, and the runway incursion prevention system (RIPS). The results showed the efficacy of the NASA Synthetic Vision System to significantly enhance pilot situation awareness for runway traffic and terrain, and substantially better pilot acceptability and trust due to integrated integrity monitors and enhanced vision sensors.

Future Research

The NASA AvSSP SVS project has since conducted an experiment examining the efficacy of 3-D exocentric multi-mode SVS navigation displays with significant positive results. Future research will focus on (1) enhancement of the dynamic tunnel concept to provide 4-D required time of arrival and required navigation performance, (2) crew coordination human factors research using SVS, (3) exocentric dynamic 3-D SVS navigation displays for

approach and missed approach rehearsal, (4) military applications of synthetic vision, (5) advanced display media, and (6) integration of SVS with other emerging NASA cockpit information displays.

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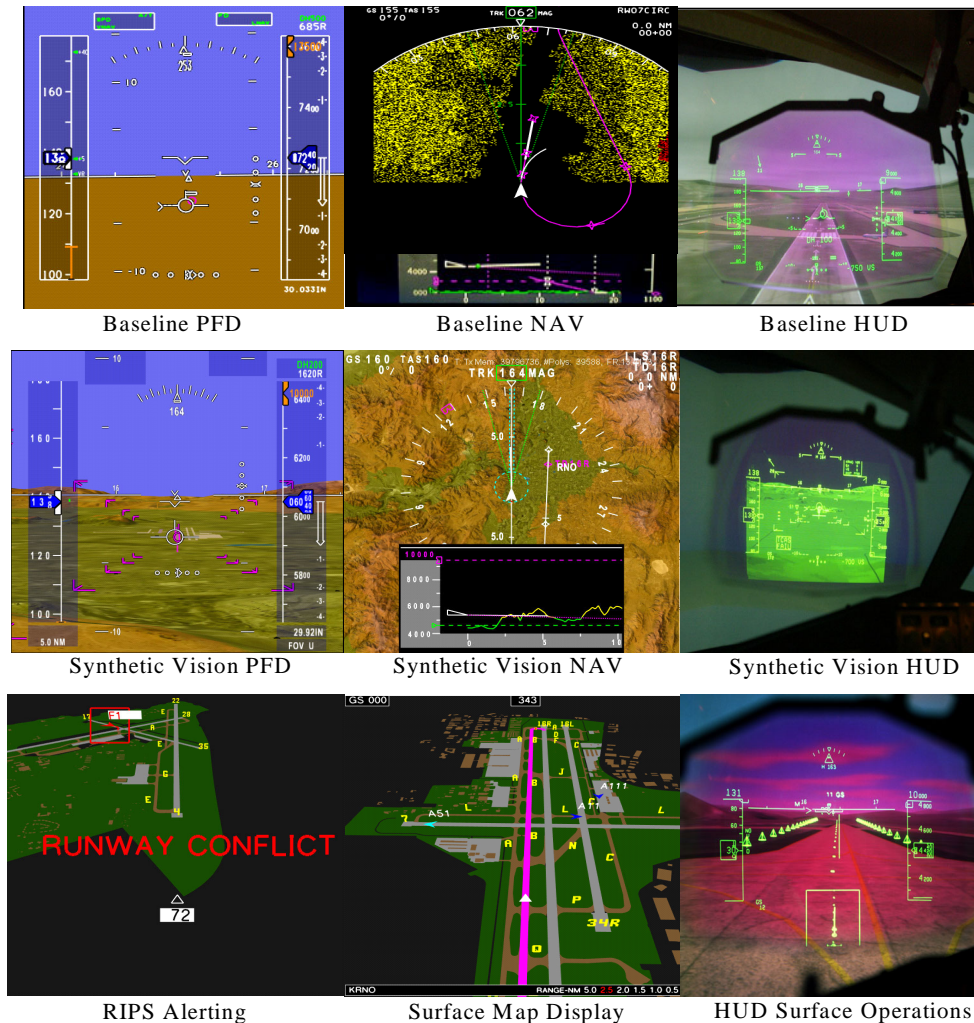


Figure 3. Experimental Display Concepts