

# SYNTHETIC AND ENHANCED VISION SYSTEMS FOR NEXTGEN (SEVS) SIMULATION AND FLIGHT TEST PERFORMANCE EVALUATION

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## Abstract

The Synthetic and Enhanced Vision Systems for NextGen (SEVS) simulation and flight tests are jointly sponsored by NASA's Aviation Safety Program, Vehicle Systems Safety Technology project and the Federal Aviation Administration (FAA). The flight tests were conducted by a team of Honeywell, Gulfstream Aerospace Corporation and NASA personnel with the goal of obtaining pilot-in-the-loop test data for flight validation, verification, and demonstration of selected SEVS operational and system-level performance capabilities.

Nine test flights (38 flight hours) were conducted over the summer and fall of 2011. The evaluations were flown in Gulfstream's G450 flight test aircraft outfitted with the SEVS technology under very low visibility instrument meteorological conditions. Evaluation pilots flew 108 approaches in low visibility weather conditions (600 ft to 2400 ft visibility) into various airports from Louisiana to Maine. In-situ flight performance and subjective workload and acceptability data were collected in collaboration with ground simulation studies at LaRC's Research Flight Deck simulator.



Figure 1: Gulfstream G450 Test Aircraft

## Background

Synthetic and Enhanced Vision Systems have been identified as NextGen enabling technologies that can provide additional margins of safety and aircrew performance in low visibility surface, arrival, and departure operations. These technologies form the building blocks for an Equivalent Visual Operations (EVO) capability. Synthetic Vision Systems (SVS) use terrain/obstruction databases to present a computer rendered view of the outside world, often on a Head-Down Display (HDD). Enhanced Flight Vision Systems (EFVS) use real-time sensor input to present an enhanced visual image of the outside view on a Heads-Up-Display (HUD).

This testing was conducted as part of a formal collaboration between NASA Langley Research Center (LaRC) and the FAA under an Interagency Agreement (IA) to ensure effective development and implementation of regulatory guidance and procedures to support the introduction and use of synthetic and enhanced vision system technologies. This work builds from and extends current operational use and certification of existing synthetic and enhanced vision systems technologies to serve as building blocks toward all-weather, low visibility operations for NextGen.

## NASA Research

One focus of NASA's NextGen research is to develop performance-based standards for SEVS technologies that create EVO *and beyond*. The first part of this challenge is the development of performance-based standards expanding the current operational approvals of SVS/EFVS. This flight test effort is one task in a multi-part test plan where each element serves as a critical piece which, when combined, meet the overall task objectives. The overall test plan tasks included:

1. Ground simulation activity specifically focused on those test objectives where flight testing is impractical or potentially too hazardous, such as runway incursion detection in low-visibility conditions.

2. Flight test activity as validation and verification – conducting what can't be properly simulated, such as “real” HUD operations, and as evaluating human-in-the-loop EFVS performance operations in actual low visibility weather.
3. Finally, analysis of these data which provide the framework which confirms, rejects, or modifies the test hypotheses and establishes human-in-the-loop test data in support of regulatory guidance material.

### ***Current EFVS Rules/Operations***

In 2004, Chapter 14 of the Code of Federal Regulations (CFR) Section §91.175 was amended such that operators with approved EFVS equipment that are conducting straight-in instrument approach procedures may now operate below the published Decision Altitude (DA), Decision Height (DH) or Minimum Descent Altitude (MDA) when using an approved EFVS shown on the pilot's HUD. The key concept under the revisions to §91.175 is that an EFVS can be used in lieu of the required natural vision from the DA/DH/MDA to 100 feet height above the touchdown (HAT) zone elevation. At the 100 ft HAT, pilots transition to natural vision to continue the approach.

### ***Proposed EFVS Ops Changes***

The joint RTCA SC-213/EUROCAE WG 79 committee drafted the DO-315A [1] document to establish minimum performance standards for EFVS operations through the approach to touchdown in visibility as low as 1000 ft runway visual range (RVR) by sole use of an approved EFVS in lieu of natural vision. Simply stated, the visual segment of the approach (100ft HAT to touchdown) can now be accomplished by using either enhanced flight visibility and/or natural vision. Past NASA research supports the viability of this expanded EFVS visual segment, indicating that using an EFVS through touchdown resulted in excellent localizer tracking performance and an improvement in glideslope tracking performance. [2]

### ***Current SVS Rules/Operations***

Currently there are no special provisions or approach credit for Synthetic Vision Systems equipage. The original regulations and procedures for a 1950's era DC-3 attitude indicator essentially

apply to the modern SVS display (Figure 2 vs. Figure 4).



**Figure 2: DC-3 Cockpit**

### ***Proposed SVS Ops Changes***

The joint RTCA/EUROCAE committee also drafted DO-315B [3] to establish minimum performance standards for possible operational credit for SVS. Unlike EFVS, the possible path for operational credit is not through revision of 14 CFR §91.175, but is based on FAA Order 8400.13 (“Procedures for the Evaluation and Approval of Facilities for Special Authorization Category I Operations and All Category II and III Operations”). Specifically, DO-315B establishes performance standards for a SVS, enabling lower than standard Category I minima or a reduction in the required minimum visibility. These DO-315B performance standards for SVS operational credit do not require the use of a HUD.

### **Objectives**

The primary objectives of the SEVS flight test are twofold and correlate to the vision technologies. The objectives were to evaluate:

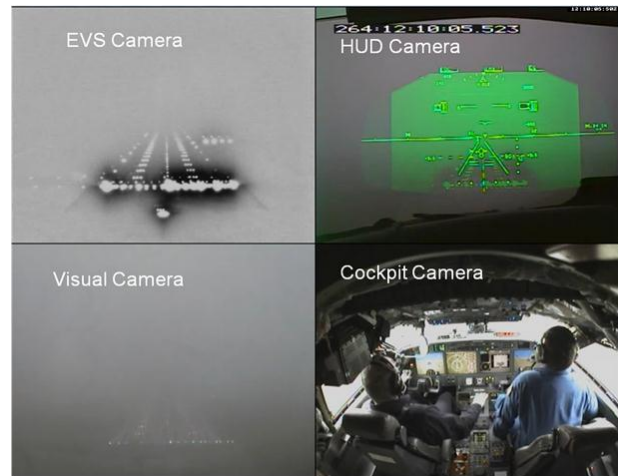
1. Operational feasibility, pilot workload, and pilot acceptability of conducting a straight-in instrument approach with published vertical guidance using EFVS during approach, landing, roll-out and runway exit in visibility of 1000 ft runway visibility range (RVR).
2. Operational feasibility, pilot workload, and pilot acceptability of conducting an instrument landing



arrangements and one single channel. See Figure 5 - Figure 7.

The nine video sources include:

1. EVS Camera (Raw FLIR image)
2. HUD Camera
3. Visual Out the Window Camera
4. Cockpit Area Camera
5. Left Seat Primary Flight Display
6. Left Seat Navigation/Multi-Purpose Display
7. Right Seat Primary Flight Display
8. Right Seat Navigation/Multi-Purpose Display
9. Combined HUD & EFV Image presented on the HUD



**Figure 5: Quad Camera Recording**

### Evaluation Pilots

Volunteers were recruited to serve as Evaluation Pilots (EP). The evaluation pilot pool included civil servant, Original Equipment Manufacturer test pilots, or Department of Defense (Military), commercial, and corporate pilots. Selected pilots received travel cost reimbursement and a small stipend with the exception of Department of Defense and other agency civil servants, which participated as part of their official duties.

The EPs met the following experience criteria:

- Each pilot held an Airline Transport Pilot rating
- Each pilot had significant HUD experience, having flown at least 100 hrs of HUD, pilot-in-command operations.
- Each pilot was type-rated in a Gulfstream G-IV, G-V, and G450, G550, or G650 aircraft and had EFVS qualifications and EFVS operational experience. Total time in the Gulfstream aircraft was greater than 200 hrs.

Six EPs participated in the flight evaluations and represented a diverse mix of experience. The pilots included two from the US Air Force, two corporate, one commercial, and one FAA test pilot. Only three of the six had any significant SVS experience or training. The average experience of the EPs was 9100 hours of flight time with an average of 28 years of flying. Most of the EP flew on multiple evaluation flights.



**Figure 6: Quad Instrument Recording**



**Figure 7: Combined HUD/EVS Image Recording**

## ***Training***

All evaluation pilots were given an approximately 30 minute briefing on the flight test details. Pilots were sent the briefing package ahead of time so they could study and task familiarize themselves allowing them to prepare any questions ahead of time. The evaluation pilot briefing covered the following topics: Experiment Background, NASA-FAA Interagency Agreement, Project Plan, Test Objectives, Schedule (multi-day), Operations Summary, EVS / SV Operations, Test Conduct & Crew Procedures, and Q&A.

Training included a cockpit and display briefing and familiarization given by the chief project test pilot, as well as a proficiency check flight. Each evaluation pilot flew with the chief project test pilot on a short flight, allowing the EP to fly several approaches with the HUD and SVS displays. During this check flight, a vision restriction device was placed in front of the EP position to simulate limited forward visibility. The vision restriction device did not restrict the side window visibility for either pilot.

## ***Procedures***

All EFVS testing was flown with the EP occupying the left seat using the HUD, a Gulfstream Safety Pilot (SP) occupying the right seat, and an additional Safety Observer (SO) occupying the center jump seat. EFVS test operations were conducted under an FAA waiver to the current Title 14 of the CFR §91.175 allowing these test flights (i.e., in an operation that is not currently approved). This waiver allowed the use of EFVS or natural vision to see the required visual references, as to continue descent below the DA/DH through landing. Safety procedures required that the SP have positive visual acquisition of the required landing references by 50 ft above touchdown elevation.

All SV testing was flown with the EP occupying the right seat and the SP occupying the left seat. The SP utilized the EFVS HUD to monitor the operation and, if the required EFVS visual references were seen, allowed continued descent below the published DA/DH to evaluate SV operations to a simulated 150 ft DH. Therefore all SV testing operated under currently approved operations (i.e. no waiver required as with EFVS testing).

All approaches were flown to runways with an operating ILS. The EPs flew straight-in instrument approaches adhering to published approach procedures (other than the waived minimums) to the runway. The Gulfstream SP, as a minimum, continuously monitored the ILS raw data. The SP also was able to monitor an EFVS repeater on the multi-function display. The intercom was operated in “hot mic” mode for the EP and SP so all comments were effectively captured in real-time

The SP continually monitored, with assistance from the Center Jump Seat SO, as required, that the airplane was stabilized on the approach to the runway. The SP and SO also verified that the aircraft was continually in a position from which to land, and could flare and land within the touchdown zone and within prescribed sink rate limits for the G450 airplane. The aircraft is equipped with dual Enhanced Ground Proximity Warning System (EGPWS) and its flight deck call-outs were audible to all. In addition, the aircraft is equipped with Runway Awareness and Alerting System (RAAS) which provided call-outs if not aligned with the landing runway or captured on the glideslope correctly.

All approaches were flown with the EP manually flying the aircraft below 1000’ AGL to a landing. The initial approach procedure was often flown with the auto-pilot engaged, following the approach procedure. Auto-throttles were used for all approaches. Detailed call-out procedures for both the EP and SP were utilized for all approaches ensuring safety throughout the approach and providing clear evidence of the acquisition of the required approach and landing visual references as per §91.175.

## ***Airport & Runway Selection Criteria***

The criterion for selecting runways was based on the desired test conditions and was constrained by safety criteria. The selection elements included: approach and runway lighting system, final approach offsets, an instrument landing system, and minimum runway dimension criteria.

In all cases, the test airport/runway met the following criteria:

- The approach has an operating Instrument Landing System (ILS)

- The runway length is at least 5000 ft long and width of at least 100 ft.
- The runway approach lighting system must be equivalent or greater than MALSR: Medium-intensity Approach Lighting System with Runway Alignment Indicator Lights
- Class B airports are excluded as testing locations due to logistic considerations.

### ***Locations of Test Operations***

All test flights originated at the Savannah/Hilton Head International Airport (KSAV) which is the location of the Gulfstream manufacturing and flight test facilities. Table 1 lists all of the airports and runways utilized in the flight test operations.

A list of target airports was agreed on at preflight to make flight plans based on the present and forecasted weather. The actual test locations were determined in near real-time from updated weather from expert weather operations support and from Automated Surface Observing System (ASOS) and Automated Terminal Information Services (ATIS) reports while in route to the target area.

### ***Test Conditions - Weather***

For EFVS operations the target visibility was 1000 ft RVR to 1/4 statute mile with a ceiling of 100 feet. The exact desired weather conditions for the test were achieved on several occasions. Over the course of multiple approaches, the visibility and ceiling naturally varied at each airport, giving a nice range of data on either side of the target conditions.

For SVS operations, the target visibility was 2400 ft or less with a ceiling of 150 ft. The desired weather conditions for the test were also achieved on several occasions. As conditions generally lifted, the evaluations changed from EFVS to SVS to collect as much data as possible. A sampling of weather conditions for data collection at the different airports is shown in Table 1.

### ***Flights Summary***

There were seven data collection flights conducted from July 20 to Oct 28, 2011. All flight time totaled approximately 38 hours with the seven data collection flights comprising approximately 35 flight hours. Data were collected at fifteen different airports and utilized 16 different runways.

There were 108 approaches flown, 81 were EFVS approaches (75%) and 27 were SVS approaches (25%). Out of the 108 approaches, 7 were culled out of the data analysis for various extraneous reasons such as: Approach Lighting System (ALS) automatically turning off, or EP mistakenly left autopilot on during much of the approach, etc. These events were anomalous and caused significant deviations from our nominal operation and therefore, were not representative of the other approaches. From the usable data set of 101 approaches, there were 71 touchdowns and 30 missed approaches for both EFVS and SVS technologies. Eight (8) of the EFVS approaches were to an offset runway (KBGM).

### ***EFVS Approach Summary***

There were 74 useable EFVS approach evaluations with 53 touchdowns, and 20 (27%) that resulted in missed approach. The 20 missed EFVS approaches were all conducted safely with the go-around decision correctly determined based on conditions.

### ***SVS Approach Summary***

There were 27 SVS approach evaluations with 18 touchdowns and 9 that resulted in missed approaches. Of the 9 missed SVS approaches, 3 missed approaches were due to the SP not having EVS lights at 200 ft height above touchdown zone elevation as there was too much weather obscuring even for EFVS ops; and therefore, the SVS evaluation down to 150 ft HAT could not occur. Of the remaining 6 missed SVS approaches; four were due to the EP not seeing the runway environment at 150ft and correctly made the go-around decision; and the remaining two missed approaches were due to the SP calling to go-around because the aircraft was not in a position to land.

## **Results**

Quantitative flight performance metrics were recorded and analyzed for each approach starting from 1000ft HAT until after touchdown or go-around. Weather information was recorded from various sources for each approach. The landing decision call altitude and go-around altitude out was noted for each approach and analyzed. Qualitative approach assessment and workload results were

recorded and analyzed as well as free form comments from the evaluation pilots.

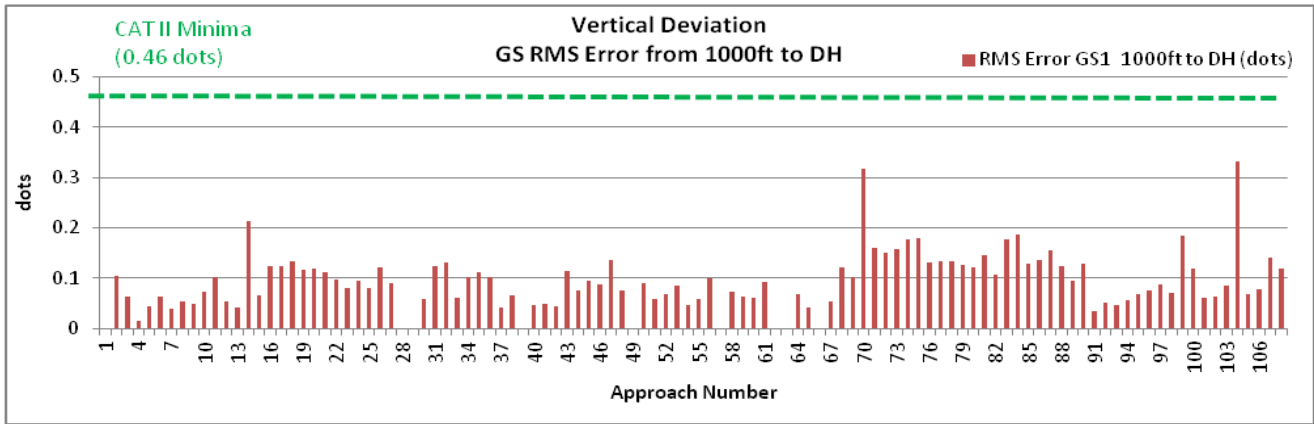
**Flight Performance**

Many approach performance parameters were analyzed including the use of root mean square (RMS) error of localizer deviation (in dots), RMS error of glide slope deviation (in dots), and the

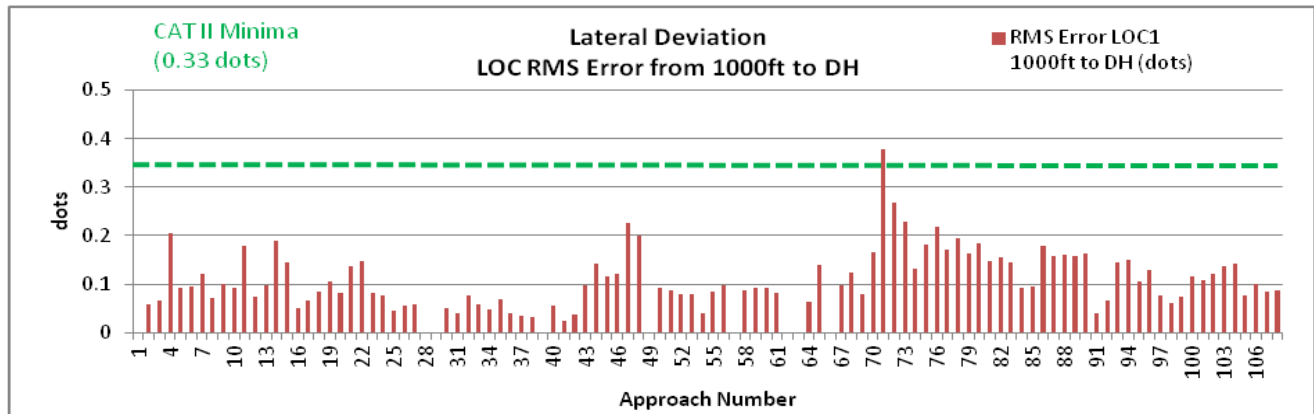
standard deviation of vertical speed (in feet per minute, or fpm). These parameters correspond intuitively to how well a stabilized approach to landing was established and maintained. The data were analyzed from 1000 ft to DA (H) for the all approach runs.

**Table 1 : Test Airports and Conditions**

Airport	Approach	Reported Visibility (SM)	Reported RVR (ft)	Reported Ceiling (ft)	Wx Notes
Shenandoah Valley Regional	KSHD ILS 05	1/4-1/2		100	OVC, FOG Thin but dense layer
Altoona Blair County	KAOO ILS 21	1/2		100	FOG OVC
Portsmouth Intl. /Pease	KPSM ILS34	1/8	900-1200	100	Fog, Broken
Bar Harbor -Hancock County	KBHB ILS22	1/4		200	Fog overcast
Greater Binghamton /Edwin A. Link Field	KBGM ILS16	< 1/4	600	100	Fog, Indefinite ceiling
Albany International	KALB ILS01	1/4		200	Mist
Vidalia Regional	KVDI ILS 24	1/4		100	Fog, Overcast
Savannah/Hilton Head International	KSAV ILS 10	1 1/4		200	Scattered thin
Acadiana Regional	KARA 34 ILS	1/4		100	Broken, Overcast Dense thin layer at 100-50'
Esler Regional	KESF ILS 27	1/4		100	Fog, Overcast
Alexandria International	KAEX ILS 14	1/4		100	Fog, Overcast
Cincinnati Muni Airport-Lunken Field	KLUK ILS 21	1/4	2400	100	Fog
Akron-Canton Regional	KCAK ILS 19	1/4		100	Freezing Fog
Youngstown /Warren Regional	KYNG ILS 32	1/8	1000	200	Freezing Fog



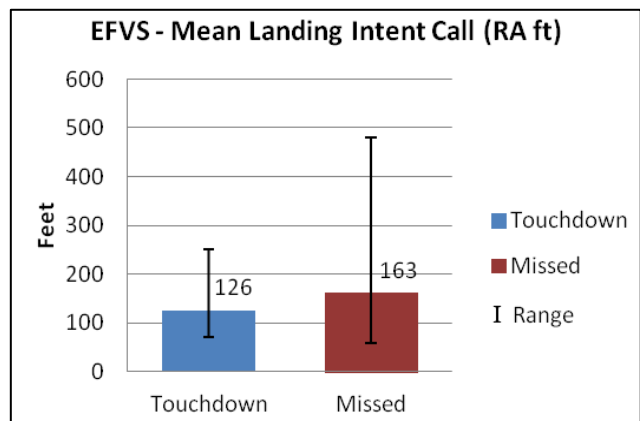
**Figure 8: EFVS Vertical Deviation**



**Figure 9: EFVS Lateral Deviation**

Figure 8 illustrates the vertical RMS error for all (touchdown & missed) EFVS approaches and Figure 9 illustrates the lateral deviation RMS Error. All were within Category II approach minima outlined in AC120.29A with the exception of one approach (#71), and even this approach, in a challenging crosswind, resulted in a safe successful touchdown. The vertical and lateral deviations metrics for SVS approaches were similar, all within CAT II minima.

As instructed, the evaluation pilots called out their landing intent and the altitude was noted. As shown in Figure 10, the mean EFVS Landing Decision Altitude call-out for touchdowns was 126 ft radar altitude vs. 163 ft for missed approaches.



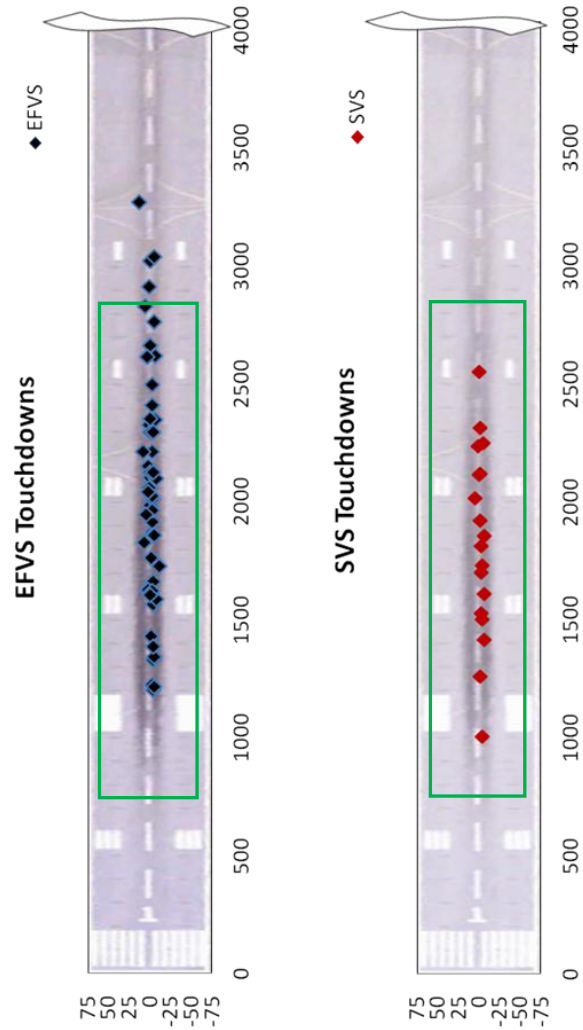
**Figure 10: Landing Intent Call-out Altitude**



Touchdown statistics were used to evaluate how effectively the pilots could land. Existing landing standards for touchdown (T/D) longitudinal position, lateral position from centerline were applied in the objective landing data analysis. Several factors were considered in this analysis and include the fact that the pilots were instructed to follow the flare cue during EFVS operations. (The flare cue does not give guidance to a specific longitudinal touchdown point. The flare cue indicates sink rate/flight path information based on the radar altimeter.) Additionally, the landings were almost exclusively flown as a touch-and-go; and therefore, EFVS longitudinal touchdown locations were expected to be slightly longer than with full stop operations. Auto-land touchdown standards (AC120-28D) are shown as a green box in Figure 11 as they pertain to the general concept of low-visibility approach and landings using guidance systems technologies; however, this comparison is for information only since they were not written specifically for manually-flown operations with advanced vision systems such as EFVS and SVS. Lateral and longitudinal touchdown position statistics are shown in Table 2 for both EFVS and SVS operations. The SVS touchdown data correspond to a visual, no HUD landing; thus, a direct comparison can be made between EFVS and natural vision landing performance (although the SVS, visual landing data are more sparse).

**Qualitative Measures**

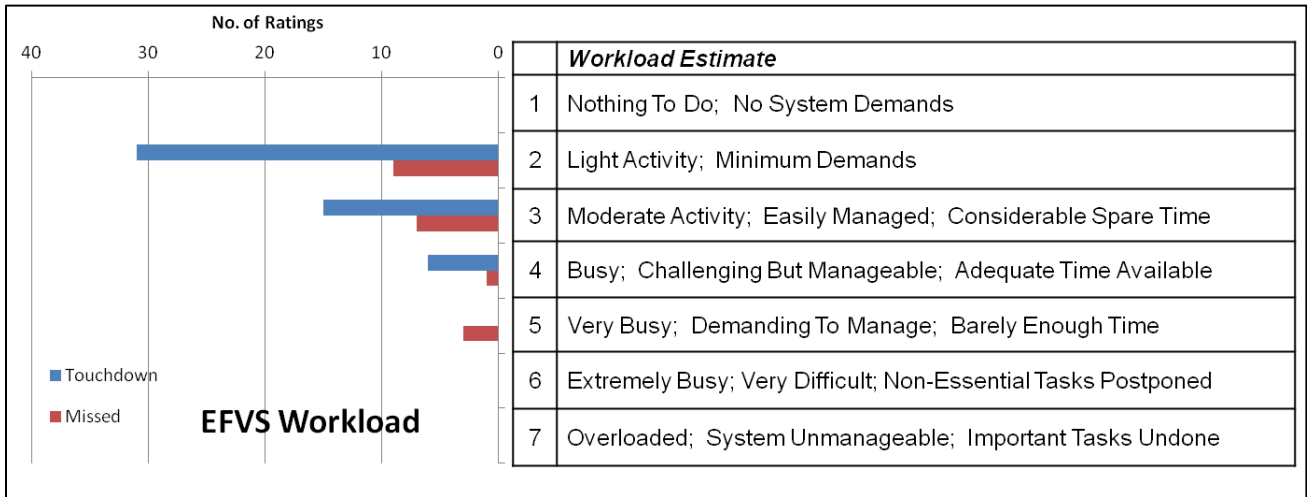
After each approach, the evaluation pilots were given a questionnaire to evaluate the approach and were free to give open-forum comments. After the flight during the post-flight debriefing, unstructured free-form comments were solicited from the evaluation pilots. In addition, the EPs were asked to provide an assessment of their display preference (EFVS, SVS, and PFD) and their perceived level of safety during SVS and EFVS operations using for the tasks that they just completed flying.



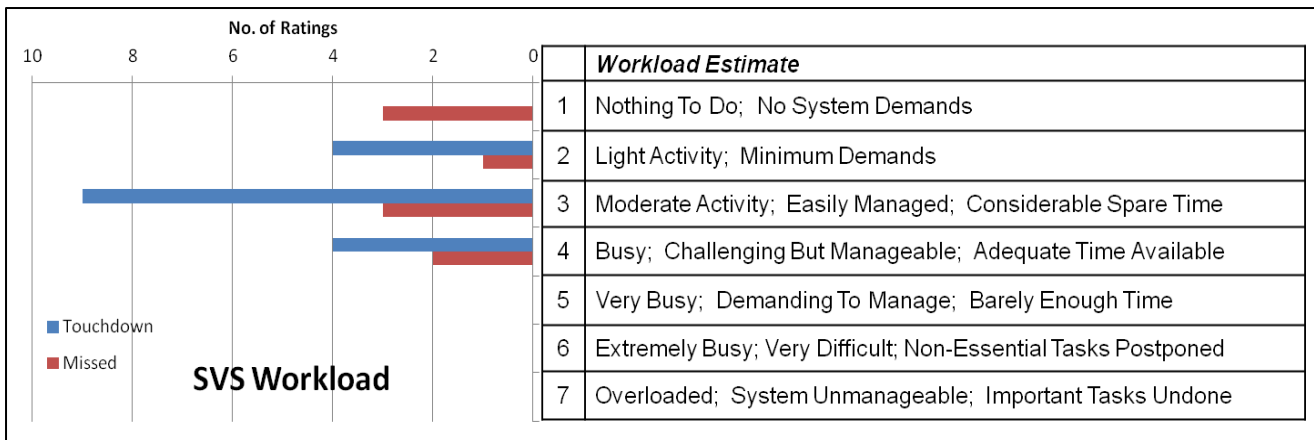
**Figure 11: SEVS Touchdown Dispersions**

Touchdown Position Statistics	EFVS		SVS	
	Long. (ft)	Lat. (ft)	Long. (ft)	Lat. (ft)
Mean	2058	3.47	1826	2.9
Max	3266	13.79	2548	6.5
Min	1198	0.19	1001	0.4
SD	501	3.28	402.3	1.99
N	53	53	18	18

**Table 2: SEVS Touchdown Statistics**



**Figure 12: EFVS Post-Run Workload Summary**



**Figure 13: SVS Post-Run Workload Summary**

Workload was assessed after each approach using the Air Force Flight Test Center (AFFTC) Workload Estimate Technique [4]. Workload ratings were evaluated by conducting separate ANOVAs for the EFVS operations and for the SVS operations. In general, for EFVS evaluations the pilots rated their workload as being ‘Easily Managed’ with ‘Considerable Spare Time’ while using the EFVS during either a landing (Mean=2.5) or a Go-Around (Mean=2.9). The workload rating summary for EFVS is shown in Figure 12. For SVS evaluations the pilots rated their workload as being ‘Easily Managed’ with ‘Considerable Spare Time’ while using the SVS during either a landing (Mean=3.0) or a Go-Around (Mean=2.4). The SVS workload rating summary is shown in Figure 13.

## Discussion

The flight test showed that pilots are able to fly EFVS approaches without the visual segment transition at 100 ft: The pilots flew the glideslope and localizer course within standards in conditions as low as 1000’RVR (53 landings) with acceptable workload. Pilots ranked EFVS as being significantly preferred for flying within low-visibility approach/landing operations over a conventional PFD. Also, pilots perceived that the level of safety was significantly better with the EFVS compared to a conventional PFD. Pilots preferred that the visual transition at 100 ft HAT (now used in the current regulation) was eliminated.

Within the small data set of 27 approaches, the pilots demonstrated operation feasibility of SVS operations with a 150 ft HAT decision height. Pilots flew the glideslope and localizer course within the standards in conditions as low as ¼ mi visibility (18 landings). Workload was acceptable while flying SVS to a lower than standard decision height of 150ft above touchdown. The SVS PFD was ranked as being significantly preferred for flying within low-visibility approach/landing operations over a conventional PFD. Pilots perceived that the level of safety was significantly better with the SVS compared to a conventional PFD.

## Lessons-Learned

A wealth of data was gathered in the flight test from the qualitative pilot comments and flight test engineer's observations of the system and pilot-in-the-loop performance. Further, invaluable lessons were also learned. For instance:

- The performance of the Kollsman II EVS sensor was generally outstanding, providing the required visual approach and landing references clearly beyond that of the natural vision.
- Actual weather flying continually demonstrates and emphasizes how non-homogeneous weather conditions can affect EFVS performance. In particular, the varying weather effects can induce blooming on the EFVS that, at times, can be objectionable to the flight crew. Research is needed to create decision aids for an EFVS crew in evaluating the ATIS or ASOS report and creating guidance as to the probability of successfully completing the approach and preparing for contingencies.
- Precipitation on the EFVS noticeably degraded the ability of the pilot to use an EFVS to complete the approach and landing.
- A flare cue driven by radar altitude was used in this flight test. Its effect could not be quantified but in general, it was referenced but not followed exactly. The flare cue might have induced more floating tendency on the landing to assist in getting lower sink rates for a touch-and-go landing.
- The influence of guidance cues and angular offsets during EFVS and SVS operations should be evaluated. Offset ILS approaches are not a common occurrence in the US but when they are

flown, how they are identified during the approach briefing and the impact that they have on the operation may be underappreciated. SVS technologies offer a great opportunity to improve the safety of offset approach operations since SVS can clearly provide a visual depiction of the runway, the approach path, and where the guidance is directing the aircraft.

- Sensor technologies for improved all-weather operations are needed. Successful approaches to landings are unlikely when the reported weather is less than 1000 ft RVR using FLIR-based technology.
- The influence of Light Emitting Diode (LED) lights for some of the runway and taxi way lights should be evaluated. The presence or absence of some airport lighting conditions was not evaluated.
- Crew resource management and crew procedures for head-down SVS operations should be evaluated. The flight test evaluations were flown without a transition of pilot-flying responsibilities as the outside visual cues emerged. Research is needed to determine the effectiveness of crew resource management, operational constructs, and display influences.

## Concluding Remarks

A team of Honeywell, Gulfstream Aerospace Corporation and NASA personnel conducted a flight test with the goal of obtaining pilot-in-the-loop test data for flight validation, verification, and demonstration of selected SEVS operational and system-level performance capabilities in actual very low visibility conditions. Nine test flights (38 flight hours) were conducted over the summer and fall of 2011. The evaluations were flown in Gulfstream's G450 flight test aircraft outfitted with the certified SEVS technology. Evaluation pilots flew 108 approaches in low visibility weather conditions (61000 ft to 2400 ft visibility) into various airports from Louisiana to Maine. The data generally verify and validate that EFVS can be used continuously throughout the approach, landing, and roll-out in visibilities as low as 1000 ft RVR in lieu of natural vision. Also, the data generally verify and validate that SVS equipage may enable a reduction in visibility or ceiling minima required for an instrument approach procedure.

This data will be used by RTCA (industry-government forum) for further development of minimum performance standards for synthetic and enhanced vision systems and will also assist the FAA in possible rule-making and regulatory guidance. Numerous research and development activities will also be spawned to further explore the data and results of this test:

## References

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## Acknowledgements

This work was jointly sponsored by NASA's Aviation Safety Program (AvSP), Vehicle Systems Safety Technologies project (Mr. Paul Krasa, Program Manager) and the FAA Human Factors R&D Project for NextGen, led by Dr. Tom McCloy, Mr. Dan Herschler, and Mr. Stephen Plishka). Programmatic support and technical advice from these groups was gratefully appreciated. The team is also grateful for the technical support of Mrs. Terry King. We wish to acknowledge the contribution of Glenn Connor, whose crucial expert weather guidance made the testing successful and efficient. Also, thanks go to Chip King as the project test pilot that led us safely through all 108 approaches and Ms. Trish Ververs for making it all happen.

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*31st Digital Avionics Systems Conference  
October 14-18, 2012*