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New Primary Flight Display Vastly Improves Situational Awareness and Accuracy of Flight

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This paper provides some of the results obtained from a series of flight tests with subject pilots comparing conventional instruments with a prototype configurable primary flight display with synthetic vision and a dynamic highway-in-the-sky flight path. Conventional instrumentation includes six primary flight instruments and a course deviation indicator to indicate instantaneous aircraft deviation left or right of the desired path. The conventional instrumentation evolved to provide the sole means necessary for a pilot to control and navigate an aircraft in instrument meteorological conditions. Flying an approach with the conventional instrumentation is *reactive* rather than *predictive*. The pilot *reacts* to changes by the aircraft on the basis of what he sees on the primary flight instruments. Originally these instruments were mechanical devices and their basic design for general aviation aircraft has not changed significantly in the past 50 years. The advent of the global positioning system and advances in electronic display technology have yielded configurable flight displays of reasonable size, good sunlight readability, high reliability, and low cost. It became worthwhile to investigate alternative concepts for the primary flight instruments as a way to reduce total flight error for precision flight.

I. Introduction

THE small aircraft transportation system (SATS) program is a partnership among NASA, the Federal Aviation Administration (FAA), U.S. aviation industries, state and local aviation officials, and universities. The SATS alliance is intended to help provide air transportation to underserved small communities and to reduce transportation times by one-half within 10 years and by two-thirds within 25 years. The SATS mission is to provide precision approach and landing guidance to small airports while avoiding expensive land acquisition and ground-based precision guidance systems. The NASA/SATS program is managed and funded through a public/private consortium made up of several different SATS Laboratories (SATSLabs). The National Consortium for Aviation Mobility (NCAM), in turn, funds the SATSLabs to perform tasks with cost share provided by SATSLab partners. The North Carolina and Upper Great Plains (NC&UGP) SATSLab formed at RTI International was tasked to evaluate a refined prototype primary flight display (PFD) and multifunction display (MFD) incorporating an advanced synthetic vision system (SVS), a dynamic pathway, novel guidance symbology for aircraft guidance, and aircraft performance information display for reducing workload and improving situational awareness.

The NC&UGP SATSLab test described in [1] evaluated a prototype PFD/MFD system and refinements were proposed from the experience gained during the evaluation described in [2]. A follow-up study [3] evaluated the performance of the refined prototype PFD/MFD to achieve elements of the SATS operational concept [4]. To this end, formal flight tests were conducted in a Piper Aztec research aircraft and in a full-mission simulator at the RTI Cockpit Research Facility (CRF) [5]). These experiments verified the ability of the SVS-equipped PFD, using a global positioning system (GPS) with a wide area augmentation system (WAAS) for navigation, to provide a guidance methodology with ample precision for a single pilot to descend to a 200 ft decision height in one-half mile visibility conditions at a nontowered municipal airport without reliance on any on-the-ground guidance equipment.

The method of flying an approach with the conventional primary flight instruments (PFI) is *reactive* rather than *predictive*. To “fly the needles” with no out-the-window cues, the pilot must note when the needle on a course deviation indicator (CDI) deviates from a centered position. Turbulence, trim settings, cross winds, and movement of the yoke will then cause the aircraft to point in a direction different from the intended flight path. The CDI needle at first shows no indication that the aircraft is moving away from the desired flight path. After a period of time, the pilot may note the path deviation of the aircraft when the needle has moved more than one or two full needle widths. By then, the aircraft can be substantially deviated from the desired flight path and now flying in a direction not appropriate to maintain the desired path. The pilot then must react to correct the nose of the aircraft by estimating a heading correction angle and turning the aircraft until it is on a new heading with the new correction angle. The pilot then waits while the aircraft to returns to center the CDI needle. Back on path, the pilot then takes out part of the heading correction angle while leaving in enough estimated heading angle correction to track the approach path.

The pilot is then reacting to the track of the aircraft on the basis of what he sees on the CDI needle. For example, one of the reactive rules of thumb the instrument pilot uses is to estimate a correction angle equal to double the deviation. Thus, a perceived 4 deg deviation calls for an 8 deg correction in the opposite direction to the deviation. Estimating too low means slow return or no return to the correct direction of flight. Estimating too high means overshooting

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the desired path and possibly overcorrecting in the opposite direction. Proper corrections take time and must be done simultaneously for horizontal and vertical deviations of the aircraft when tracking two needles indicating deviations from the flight path and from the glide slope. A pilot may repeat this process many times while flying an instrument landing system (ILS) approach down to a decision height, the altitude where a decision must be made to transition to visual flight or abort the approach. If the approach is not straight in, such as an ILS approach, but has multiple segments some of which could be curved as proposed for GPS approaches, the workload could become overwhelming for the pilot. Under high workload or slowed reaction times, such corrections can cause overshooting or “scalloping” horizontally and vertically down the flight path. Both deviations contribute significantly to the total flight error.

The highway-in-the-sky (HITS) is a three-dimensional representation of the desired flight path on a perspective flight display. A tunnel is sometimes presented and displayed as linked rectangular hoops over a pathway, but the pathway can also be represented with brackets, goalposts, or a series of rectangle corners or “crow’s feet” showing a “road” along the desired route. One of the primary objectives of the HITS perspective symbology is to present an intuitive flight system to the pilot. Another objective of the HITS design was to create a system that requires very little training to understand and to use well enough to fly a high-quality approach.

The HITS method of flying an approach is predictive rather than reactive. While flying the approach from the HITS display, a pilot does not need to perform any of the mental calculations as required for a CDI approach. The effects of turbulence, trim settings, cross winds, and movement of the yoke, which can alter the aircraft heading, can be seen immediately from the HITS pathway and the needed corrections to the controls become intuitive and automatic from observing the display. With the HITS overlaid on a SVS display, the pilot is continuously aware of the position of the aircraft along the desired flight highway and altitude above the outside terrain and simply moves a guidance symbol back into the HITS guidance frame box to immediately correct the aircraft heading and altitude.

II. Flight Test Procedures

The simulation and flight phases of these experiments use basically the same cockpit equipment for piloting and navigating the aircraft. To evaluate the performance of the PFD technology to achieve the SATS lower landing minimum (LLM) operational concept, research flights were conducted in a Piper Aztec flight test aircraft (Fig. 1) that operates in conjunction with the RTI Cockpit Research Facility, the NC&UGP SATSLab’s Mobile Digital Information Facility, and NASA’s Digital Information Facility. The CRF simulator at RTI and an Aztec research aircraft at Flight International are equipped with the same PFD with an advanced SVS and the HITS. The simulator and Aztec both use a CNX-80 navigator linked to a MX-20 MFD. The Aztec aircraft is equipped with conventional instrumentation on the left side of the cockpit instrument panel and the same PFD instrumentation as used at the CRF mounted on the right side of the aircraft on a noninterfering basis (Fig. 2). The aircraft performance model in the RTI CRF simulator is a Piper Malibu PA-46.

Modifications to the Aztec include a state-of-the-art MFD, GPS navigation unit, universal access transceiver (UAT) data link transceiver, air data attitude heading reference system (ADAHRS) and associated magnetometer, research PFD, and a Graphite™ computer. The MFD is a United Parcel Service-Aviation Technologies (UPS-AT) MX-20 with additional keypad input. The GPS navigator is a UPS-AT GX-60. The UAT provides a data link system, operating on the approved research frequency of 966 MHz, which provides broadcast services for Automatic Dependent Surveillance-Broadcast, Traffic Information Services-Broadcast, and Flight Information Services-Broadcast. The flight test aircraft system includes a low-cost Seagull ADAHRS that is integrated with the MFD and PFD displays. The installation includes a High Bright™ 10.4 in. liquid crystal display for the synthetic vision display for the PFD as shown in Fig. 2. The terrain display is based on data from the U.S. Geological Survey and the HITS pathway displayed within the PFD is selected from a preprogrammed onboard “approach library” or from a standard approach programmed in the CNX-80 GPS navigator.

Fig. 1 Flight International Aztec research aircraft.

a) b)

Fig. 2 The Aztec: a) conventional gauges, and b) installation of the SVS PFD.

The pilots flew the research flight missions from the Newport News–Williamsburg Airport (PHF) to either the ILS approach for runway 7 at PHF or the GPS approach to runway 20 at nearby Wakefield Municipal Airport (AKQ). All flights were conducted in visual flight rules (VFR) conditions with a safety pilot, but with the subject pilots operating under restricted out-the-window vision providing simulated instrument meteorological conditions down to a 200 ft decision height. A flight international differential GPS system that uses an accurately known station position at PHF is accurate to within 1 m. The differential GPS system was used for the reference positioning data when evaluating total flight error (TFE). The flight data acquisition equipment was used to record the performance of the pilots flying the three ILS approaches using conventional ILS instruments and the three approaches using the SVS/HITS display.

Pilots were responsible for all navigation with both cockpit configurations, i.e., no radar vectors were to be given. They were also instructed to use checklists for proper procedures for gear, flaps, and climb power and proper power setting for cruise. Use of the autopilot was not permitted in this study in the CRF or in the Aztec. The instructor pilot discussed the complete mission and manner of flying the approach with the subject pilots in the preflight briefing. For the missions to AKQ, the pilots were tasked with flying to the TEBOE initial fix for AKQ and shoot the “T-approach”: TEBOE, NOXEE, MILUE, then to runway 20 (T-approach and fixes shown in Fig. 3).

III. Test Results

Results from the tests are summarized in three sections: horizontal flight path errors, vertical flight path errors, and a statistical analysis of the flight data and of the postflight pilot survey. The 22 subject pilots used in the tests were all instrument rated and some had considerable experience in the use of needles for flying ILS approaches, but none had much, if any, experience in the use of a

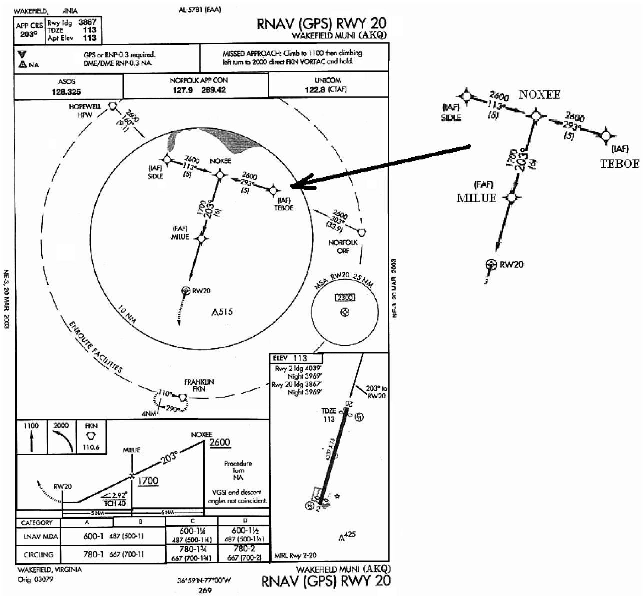


Fig. 3 Standard FAA approach plate for Wakefield.

HITS display. Some were certified instrument instructors, some had flight experience ranging from 1000 to 10,000 hours of flying time, but the majority (15) of the pilots were typical low-time instrument rated pilots. Each pilot who served as a test subject volunteered for the experiment. The Aztec pilots received no simulator training using the HITS and training consisted mainly of an ad hoc description before flight or during taxi out. Most of the pilots flying the simulator were given some practice time with the both the HITS and conventional instrumentation systems. Those practice runs that were made by the pilots were removed from the data presented in the tests. A total of 132 approaches were flown in the experiments, half with the HITS and half with conventional instruments.

For graphical representation of the recorded flight test data from the aircraft flight path, the spatial coordinate reference frame is taken as distance to touchdown along the nominal runway centerline, cross track deviation perpendicular to the runway centerline, and altitude above the runway touch down point. The origin of this three-dimensional coordinate reference frame is thus located at the touch down point on runway 7 at PHF and on runway 20 at AKQ. A positive horizontal position means the aircraft is to the left of the runway centerline. The left end of the flight path is negative corresponding to aircraft position at approach intercept. The origin at the right end corresponds to the touch down point of runway 7 at PHF and runway 20 at AKQ.

A. Horizontal Flight Path Error Results

Course deviations indicated by the CDI for flying the ILS are angular deviations. Therefore, the flight path traces will fall within two converging limit lines corresponding to the limiting pathway position along the localizer path. Full-scale deflection of a CDI needle, left or right, would be five dots, or scale markers, on a typical CDI scale. A two dot deflection on the CDI is usually accepted by pilots as sufficient deviation from the desired flight path to warrant considering terminating the approach. All of the ILS approaches to PHF on the conventional instruments were within a two dot deflection flight path limit and the approaches on the PFD with HITS were all well within the spread of the conventional instruments. The amount of the spread will be detailed in the section on flight technical error (FTE) analysis.

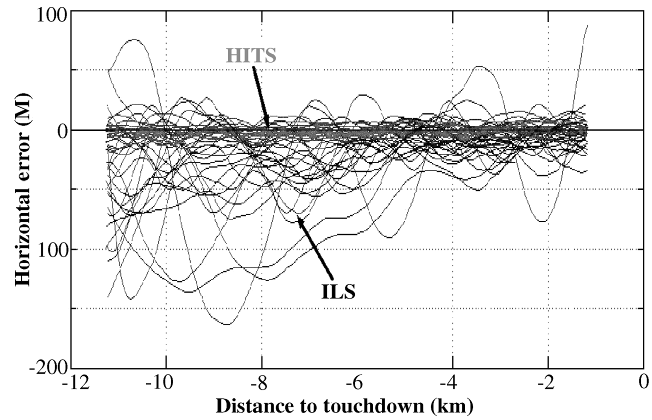
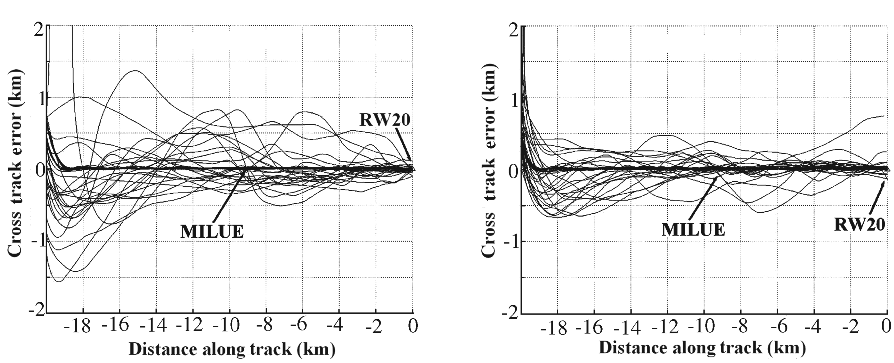


Fig. 4 Flight path error horizontal for ILS approaches at PHF.

Course deviations indicated by the CDI needle for flying the GPS approach to AKQ are linear deviations. Therefore, the flight path traces will be within two parallel lines corresponding to the limiting pathway positions along the GPS approach path. For the AKQ flights, the CRF flight paths are consistently within ± 1.6 km (± 1 mile) of the nominal flight path. The Aztec flight paths are consistently within ± 0.6 km (± 0.4 mile) of the nominal flight path. Overshooting at the intermediate fix, NOXEE is evident. Pilots quickly returned to the nominal flight path after NOXEE, getting closer to nominal as they passed the final approach fix (FAF) MILUE, and approached the missed approach point (MAP).

TFE is a combination of both flight technical error (pilot skill and influences such as crosswinds and turbulence) and navigational system error [inherent GPS or radio beacon system errors, see [6]]. Figure 4 shows the horizontal component of the TFE or distance of the aircraft from the nominal flight path. In Fig. 4, the horizontal error data is shown with a positive error meaning an aircraft position to the left of nominal. As can be seen, the HITS errors are well within the error spread for the ILS approaches.

Figure 5 shows the horizontal or cross track flight path error for all the AKQ approaches. The CRF flight paths for the conventional instruments are consistently within ± 1.6 km (± 1 mile) of the nominal flight path. The Aztec flight paths using conventional instruments are consistently within ± 0.6 km (± 0.4 mile) of the



a) Path error (CRF)

b) Path error (flight)

Fig. 5 Flight path error horizontal for GPS approaches at AKQ.

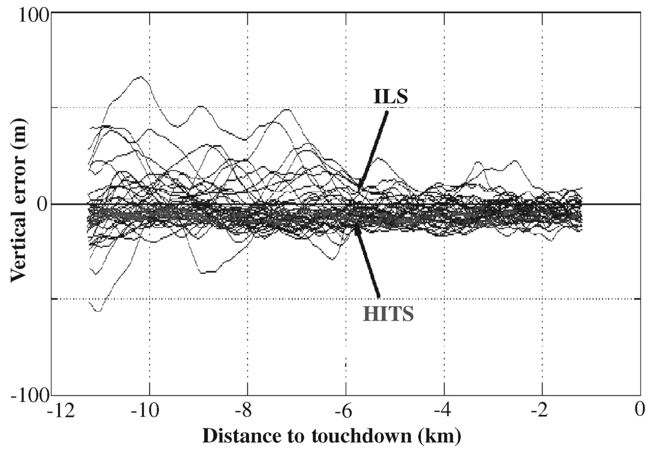


Fig. 6 Vertical flight path error for approaches at PHF.

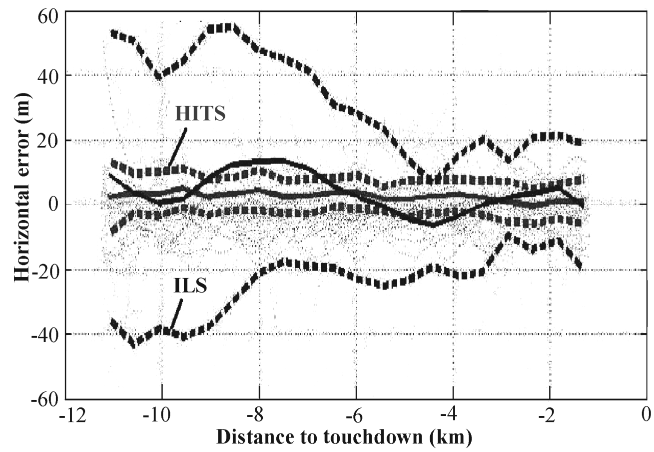


Fig. 8 Mean and standard deviation of horizontal error for approaches at PHF.

nominal flight path. Overshooting at the intermediate fix, NOXEE is again evident. Pilots quickly returned to the nominal flight path after NOXEE, getting closer to nominal as they passed the final approach fix at MILUE, and approached the MAP. The better accuracy in flight compared with the CRF is believed to be due to pilot realization that the aircraft provided a more realistic feel in flying in instrument conditions.

The horizontal error tracks in Fig. 5 for the PFD instrumentation show a dramatic improvement over the conventional instrumentation. The CRF tracks are within a spread of 100 m and the Aztec flight paths are consistently within a spread of 600 m just after NOXEE and very quickly drop to less than 100 m.

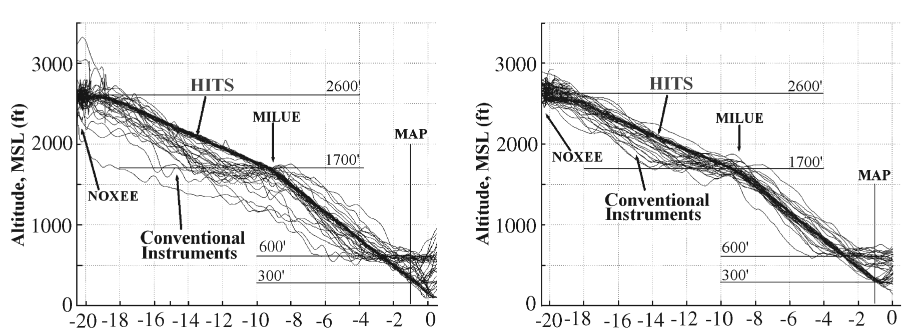
After overshooting the turn at NOXEE, the pilots on conventional instrumentation failed to stabilize on track or stabilized slowly. The CRF conventional instrumentation approach errors were between ± 1.5 km (± 0.9 mile) after NOXEE and down to $-0.25/+0.5$ km (a spread of 0.5 mile) as the pilots approached the MAP. The spread of the conventional instrumentation approach path errors in the Aztec were within ± 0.7 km (± 0.4 mile) of the nominal flight path and getting closer to nominal as they approached the MAP. The error spread for pilots on the PFD instrumentation system stabilized much more quickly after the turn at NOXEE than for pilots on the conventional instrumentation.

B. Vertical Flight Path Errors

Errors in the flight paths in the vertical direction are shown in Fig. 6 for the PHF approaches. The improvement in vertical control of the aircraft while on the PFD instrumentation compared with the conventional instrumentation is very apparent in this figure. Deviations from the glide slope as indicated by a CDI for flying the ILS to PHF are angular deviations. Therefore, the flights will fall within two converging limit lines corresponding to the limiting pathway position along the localizer glide slope. Full-scale deflection of a CDI needle, up or down, would be five dots, or markers, on a typical CDI scale. A two dot deflection on the CDI is usually accepted by pilots as sufficient deviation from the desired flight path to warrant considering terminating the approach. All of the ILS approaches to PHF on the conventional instruments were within a two dot deflection flight path limit and the approaches on the PFD with HITS were all well within the spread of the conventional instruments.

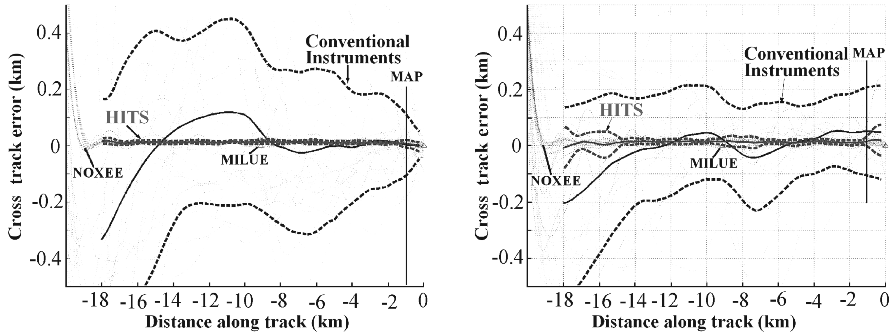
Profiles of the flight paths at AKQ in the vertical direction are shown in Fig. 7 for the conventional and PFD instrumentation approaches. The improvement in vertical control of the aircraft while on the PFD instrumentation compared with the conventional instrumentation is very apparent in this figure. The minimum descent altitude at NOXEE is 2600 feet and the pilots on the conventional instrumentation consistently went below this minimum altitude, some by as much as 500 feet. At MILUE, the published minimum altitude is 1700 feet and again pilots consistently went below this minimum, some by more than 500 feet. The minimum descent altitude (MDA) at the approach end of the runway is 600 feet for the conventional instruments and again pilots were consistently going below this minimum by as much as 100 feet. The HITS pathway is a compelling reminder of where the aircraft is relative to the desired altitude. Pilots tended to keep the predictor symbol above the pathway at all times and, hence, very seldom let the aircraft drop below the desired altitude by any significant amount.

Pilots on the PFD instrumentation flew a much more consistent approach path and did not significantly go below the minimums at NOXEE, MILUE, or the MAP. By staying on the HITS pathway the pilots could easily make a 600 ft nonprecision MDA. The pilots on the PFD instrumentation were asked to fly to a 300 ft MDA to verify that a precision type approach (200 ft above ground in one-half mile visibility) could be flown to a typical nontowered airport. All of the pilots successfully flew a precision type approach and none went below the 300 ft MDA minimum before the MAP.



a) Final approach profile (CRF) **b) Final approach profile (flight)**

Fig. 7 Vertical flight path profiles for approaches at AKQ.



a) Mean and standard deviation (CRF) b) Mean and standard deviation (flight)

Fig. 9 Mean and standard deviation of horizontal error for approaches at AKQ.

Figure 8 compares results from a statistical analysis of the FTE for the two instrumentation systems. Shown are the statistical average and the standard deviation in FTE about the nominal flight path. The broken lines show the standard deviations left and right of nominal for the conventional instrumentation and PFD instrumentation. The solid lines are the mean deviation left and right of nominal for the conventional instrumentation and PFD instrumentation.

The standard deviation curves also reflect the same influence of the reactive nature of flying with conventional instrumentation. Course deviations from reacting to the needles are indicated by the two converging broken lines in Fig. 8 for the conventional instrumentation. The large average spread to the left in the figure show the pilots had the most error as they began to react to the CDI needle after the turn at NOXEE but were becoming more adept at reacting to the CDI needle by the time they reached the MAP.

The results in Fig. 9 bring out two important points to be made regarding a pilot flying with conventional instrumentation compared with the PFD instrumentation. The first point is the dramatic improvement in accuracy gained from flying the approach with the PFD/MFD system as compared with conventional instruments. The CRF flight path data used to generate the standard deviation curves in Fig. 9 for the conventional instrumentation flight paths swings between ± 1.5 km (± 1 mile) resulting in standard deviations between ± 0.5 km as shown in Fig. 9. The flight path traces for the PFD instrumentation in comparison hover around ± 25 m resulting in standard deviation curves in Fig. 9 that hover around 0 km of error.

The second point comes from the shape of the mean deviation curves, which shows the reactive nature of flying with conventional instrumentation. The mean deviation from the nominal flight path begins with a negative deviation as pilots overshoot at NOXEE. Once that turn was made, pilots on conventional instrumentation estimate a heading correction to apply to the needles to return to the nominal flight path. These corrections are reflected in the mean deviation curve passing through a zero value of mean deviation. Once back to the nominal pathway, the pilots react again to the needles to take out part of the heading correction. On average, the pilots did not take out enough correction as reflected in the mean deviation curve moving to the left of the nominal pathway. Again reacting to the needles, the pilots reestimate a new correction and the deviation curve shows that the aircraft, on average, returns to the nominal flight path at a second zero-deviation point. Thus, the pilot workload does not let up as they continue to react and correct along the entire approach to the MAP. On the other hand, the mean deviation curve from the PFD instrumentation flights show a small spread after an overshoot at NOXEE followed by a quick return to the nominal approach path. With no additional workload, no oscillations appear in the mean deviation curve and FTE hovers around 0 km of deviation from the nominal flight path down to the MAP.

A statistical analysis of pilot responses to a postflight survey questionnaire comparing the two instrumentations systems was performed. A results summary was also made of pilot performance comparison between the conventional and the PFD instrumentation. The GPS/WAAS position of the aircraft was recorded for both the simulator and the Aztec flights and compared with the nominal flight path. A statistical analysis was performed on the flight path traces and the FTE to compare performance of the two instrumentation systems.

The entire flight path position data from the PHF approaches with the HITS, from glide slope intercept to decision height, were included in a statistical analysis. Statistical mean values of the data for TFE, navigational system error (NSE), and FTE for all of the HITS approaches were 2.6 m for horizontal TFE, 0.4 m for vertical TFE, 1.0 m for horizontal NSE, 0.2 m for vertical NSE, 1.6 m for horizontal FTE, and 0.2 m for vertical FTE. Statistical standard deviations of the data for TFE, NSE, and FTE for all of the HITS approaches were 6.0 m for horizontal TFE, 4.6 m for vertical TFE, 1.3 m for horizontal NSE, 2.8 m for vertical NSE, 6.3 m for horizontal FTE, and 4.3 m for vertical FTE. It should be noted that the NSE and TFE are not completely independent in a rigorous statistical analysis sense.

Because of the limitations of the collection equipment, only the TFE for the ILS approaches flown with conventional instruments was recorded. The NSE and TFE data could not be extracted. A similar statistical analysis of all the ILS approach data was used to get overall statistical mean and standard deviation values for the ILS approaches. Statistical mean values of TFE for the conventional instrumentation ILS approaches were 3.3 m for horizontal TFE and 2.0 m for vertical TFE. Similarly, statistical standard deviations of TFE for the conventional instrumentation ILS approaches were 29.6 m for horizontal TFE and 13.3 m for vertical TFE.

The TFE for the HITS flown approaches was nearly constant all along the approach flight path, whereas the TFE for the ILS flown approaches decreases as the aircraft approaches the decision height. A comparison of HITS and ILS approaches was made where the ILS FTE is comparable, that is the ILS data near the 200 ft decision height at the approach end of the flight paths was also analyzed. Statistical mean values of TFE near decision height were 0.7 m for horizontal ILS, -0.1 m for vertical ILS, 0.8 m for horizontal HITS, and 0.0 m for vertical HITS.

An overall statistical analysis of the FTE data collected on the AKQ approaches gives numerical results to quantify what is seen graphically in the previous figures. For horizontal deviation on the approach with conventional instrumentation, CRF, the mean was 31 m and the standard deviation was 317 m; with PFD instrumentation, CRF, the mean was 10 m and the standard deviation was 9 m; for Aztec flights with conventional instruments, the mean was -2.8 m and the standard deviation was 217 m; for Aztec flights with HITS, the mean was 12 m and the standard deviation was 23 m.

The mean values for the conventional instrumentation need some explanation. The mean error curves in Figs. 8 and 9 oscillate about the zero mean error line as the pilots react to the CDI needle as discussed above. The mean error value is a sum of the negative and positive error oscillations. A mean error of 31 m for the conventional instrumentation, CRF, above would appear to indicate that on average, over the entire approach, the pilots were off by only 31 m when in reality they were off course at times by 10 times that amount. The mean error for the PFD instrumentation of 10 m was also the sum of positive and negative errors, but the mean error for the PFD instrumentation was never much greater than 10 m along the entire flight path. It is therefore safe to say that the mean error for the conventional instrumentation was 30 times greater than the PFD instrumentation error at times along the approach to the MAP.

The statistical analysis of the survey data collected indicates that the sample of pilots used in this study is representative of the range of experience and proficiency typically found in the general aviation community. To assess whether more experienced pilots were rated any differently by observers, a Pearson correlation coefficient analysis was conducted between five proficiency measures and the observer's ratings on situational awareness (SA) and workload. There was no significant correlation between these five measures and the observer's ratings, meaning that pilot experience was not a significant factor in assessing SA and workload. Therefore, if differences are found in SA/workload ratings between pilots using conventional display and the PFD, they cannot be attributed to differences in pilot experience/proficiency.

Observers subjectively ranked and recorded each pilot's workload during the simulated flight. The observers rated workload for each pilot on a five-point Likert scale that ranged from one to five, with one being equal to extremely low and five being equal to extremely high. The observers paid particular attention to the following considerations in judging workload: 1) deviation from assigned flight path, 2) procedural errors, 3) judgment errors, and 4) communication lapses/errors. For each pilot, the observers' workload ratings were averaged to give one score per pilot for analysis purposes.

A related scores t-test identifies if mean differences in workload between conventional instrumentation and PFD instrumentation were significant, indicating that workload was greater for conventional displays. A related scores t-test was performed on workload ratings obtained from observers during the flight test to identify mean differences in workload between conventional instrumentation and PFD instrumentation. Results of this analysis indicated a significant difference in workload between instrumentation systems, indicating that workload was greater for conventional instrumentation.

Observers rated each pilot on three levels of SA as defined by Endsley's taxonomy of SA [7]. Level one SA includes perception of status, attributes, and dynamics of relevant elements in the environment. Level two SA goes beyond that of level one and includes an understanding of the significance of those elements in light of one's goals. Finally, level three SA includes the ability to project the future actions of the elements in the environment at least in the very near term. Level three forms the highest level of SA and is achieved through knowledge of the status and dynamics of the elements and a comprehension of the situation (both level one and level two SA). For each of the three levels, a five-point Likert scale was used in which SA was rated from one (extremely low) to five (extremely high). Observers were asked to pay particular attention to the following considerations in determining SA: 1) throttle/prop/mixture, 2) airspeed, 3) pitch/roll/heading, 4) altitude, 5) course changes, and 6) using the display effectively for both the conventional and PFD instrumentation systems.

Repeated measures analysis of variance was performed on data gathered during the simulation flight to identify significant differences in SA ratings between pilots using conventional instrumentation or PFD instrumentation. Results indicated significant differences in SA across three levels. A post hoc analysis using the Tukey test determines significance between specific levels of SA. The post hoc analyses showed significant differences between each level of SA for conventional instrumentation and each level of SA for the PFD instrumentation. The SA was higher for the PFD instrumentation across all three levels of SA measured in this study compared with the three levels of SA for the conventional instrumentation.

IV. Conclusions

The results of these experiments show that an aircraft equipped with a PFD with HITS superimposed on a SVS terrain image, and with a computed guidance cue to aid in tracking, provides a viable technique allowing a pilot to confidently and consistently control an aircraft. The subject pilots were able to fly significantly more accurate precision approaches with the HITS than with the conventional PFI system. The HITS approaches were within 6 m horizontally and 4 m vertically of the nominal approach path from glide slope intercept down to a 200 ft decision height under simulated limited visibility conditions. The evaluation tests showed the performance of the advanced PFD technology does indeed provide a viable means to achieve the SATS LLM operational concept of allowing a pilot to confidently and consistently fly an approach to a 200 ft decision height. Furthermore, the HITS display symbology provides a predictive approach method, as opposed to the reactive PFI method, for controlling the aircraft.

The pilot survey results collected in this experiment reflected the pilots' assessment that consistent high quality approaches can be flown with the HITS with less training than usually associated with the conventional PFI system. The surveyed pilots felt that the HITS display's intuitive architecture provided increased situational awareness, decreased pilot workload, and produced more accurate instrument flying than the conventional primary flight instrument techniques. With less workload and stress, the pilots felt they had more time to attend to other cockpit duties and more time for higher quality interaction with air traffic control. This gave the pilots more confidence in safer cockpit operations and associated improved flight safety and situational awareness.

The pilots were able to fly significantly more accurate GPS approaches with the PFD instrumentation than with conventional instrumentation. From the recorded flight path data for approaches to AKQ in the CRF, the conventional instrumentation approach paths were spread out horizontally as much as 1.7 nm about the nominal, whereas the PFD instrumentation flight paths were spread out to less than 100 m. In the Aztec, the conventional instrumentation approach paths were spread out horizontally as much as 0.6 nm. The PFD instrumentation flight paths in the Aztec were all within a spread of 600 m just after the turn onto the approach and very quickly dropped to less than 100 m.

The mean and standard deviation results for the flight path error showcase the reactive nature of flying with conventional instrumentation and the predictive nature of flying with the PFD system with computed guidance. From the CRF flight error results, the standard deviation for the conventional instrumentation was 317 m and 9 m for the PFD instrumentation, a ratio of 35 to 1. For the Aztec, the standard deviation for the conventional instrumentation was 217 m and 23 m for the PFD instrumentation, a ratio of 9 to 1.

In the vertical dimension, it is significant to note that pilots on the conventional instrumentation frequently went below minimum altitude restrictions by as much as 150 m (500 ft) at the FAF and by as much as 30 m (100 ft) at the MAP, whereas the PFD approaches were consistently at or above MDA at the FAF and at the MAP.

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