Operational Experience with and Improvements to a Tunnel-in-the-Sky Display for Light Aircraft

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ABSTRACT

A prototype GPS-based primary flight display has been developed at Stanford and is being used to evaluate operational issues through piloted simulation and flight testing. The display makes flying by instrument reference safer and easier by presenting an “out the window” view of the world, allowing the horizon, runway, and desired flight path to be seen even when flying in clouds. The flight path is depicted on the 3-D display as a tunnel through which the pilot flies the airplane, and predictor symbology provides seamless guidance along straight and curved flight paths. Differential GPS data is provided by the Stanford Wide Area Augmentation System (WAAS) and Local Area Augmentation System (LAAS) prototypes. Flight testing on a four-seat Piper Dakota has demonstrated enhanced ease of use over current displays, precise navigation on complex flight paths, and the potential for increased safety through situational awareness. Recent flight testing has also highlighted several operational issues that are addressed in this paper.

The improvements described here were evaluated with simulation and flight testing on increasingly challenging flight profiles. Instrument approaches (including missed approaches and holding patterns) were flown with both conventional instrumentation and the tunnel display to allow comparative testing while maintaining compatibility with current ATC operations. Non-precision procedures were

improved by the addition of glideslope information to provide a stabilized final approach. Flight technical error (FTE) and runway-relative position are used as the basis for comparison. The display was also used to fly profiles typical of those used in the remote sensing field to explore the ultimate achievable path following accuracy for such niche markets. This data is expected to be useful in the development of TERPS standards for future instrument approaches.

INTRODUCTION

Primary flight instrumentation on current general aviation and business aircraft has been fairly static over the past 50 years. Individual instruments were designed to display flight information based on the technology used to acquire that information, resulting in a loosely integrated set of individual gauges and dials which display aircraft state. A competent pilot can scan the gauges and dials to create a mental image of aircraft state; however, for workload intensive tasks such as flying precision approaches, this scan requires a fair amount of concentration even for experienced pilots. New opportunities for making flying safer and easier are offered by the accurate three-dimensional (3-D) positioning systems such as WAAS and LAAS. With relatively inexpensive LCD technology and attitude systems appearing on the market even now, creating a display that fully utilizes this 3-D information by presenting the pilot with a perspective picture of the outside world, along with desired flight path and runway information, is a goal within reach.

BACKGROUND

A good overview of the difficulties associated with flight solely with reference to instruments is given in (Barrows, et. al, 1996). The general problem revolves around the pilot's need to maintain situational awareness (exact knowledge of the aircraft's state, including position and altitude, location with respect to the desired flight path and profile, aircraft system status, etc.) while flying within clouds or fog. The loosely-integrated set of dials, gauges, and indicators in today's light aircraft can be difficult to use in instrument flight conditions. A good example is the Instrument Landing System (ILS) receiver and display, the most accurate landing system normally used in light aircraft (FAA AIM, 1990). The ILS display consists of two needles that indicate lateral and vertical angular deviations from the straight-in approach path. A significant amount of training and skill is required to smoothly fly an ILS approach by hand. Because the missed approach leads the aircraft away from the straight-in approach path, the ILS is of no use during this procedure. These characteristics all contribute to a more fundamental problem: that it is easy to lose situational awareness when using an ILS needle indicator.

To enhance situational awareness, researchers have been working for some time on displays that integrate the many data sources needed for flight with a 3-D perspective view of the outside world. The desired flight path is presented as a tunnel or series of symbols for the aircraft to fly through and has been called a “highway-in-the-sky”, “pathway-in-the-sky”, or “tunnel” (Wiener, et. al., 1988; Grunwald, et. al, 1984; Moller and Sachs, 1994). Most of the work on 3-D perspective displays has centered on laboratory simulation or heavily-instrumented flight test aircraft (Grunwald, et. al., 1984; Bray and Scott, 1981). Our goal was to demonstrate the practical application of enabling technologies to a system that addresses the operational, budget, power, and form-factor constraints of light aircraft.

SIMULATOR STUDY

As part of our overall investigation into possible improvements in flight display technology, we conducted a simulator study to investigate three possible improvements to conventional general aviation flight instruments: the track symbol, the glideslope predictor symbol, and a pathway-in-the-sky display (each discussed below). By looking at pilot performance in flying instrument approaches with each of these enhancements and comparing it to performance while flying conventional instruments, we hoped to measure any significant improvements gained with the new displays.

Apparatus and Experiment. In order to investigate candidate flight display symbology, we utilized an FS-100 PC-based simulator manufactured by Jeppesen emulating a Beechcraft Bonanza driving a high-resolution, antialiased display. The display update rate (15 Hz) was subjectively considered smooth enough for this investigation. For the control case, the subject pilot flew approaches with the display emulating conventional instruments, i.e. airspeed indicator, attitude indicator, altimeter, turn coordinator, horizontal situation indicator (HSI) with glideslope display, and (non-instantaneous) vertical speed indicator. Distance Measuring Equipment (DME) display and marker beacons were also displayed, although they were not required for the simulated approach flown. The pilot had a conventional control yoke (since all flight was autocoordinated, rudder pedals were not used), a slider lever controlling throttle, and a rocker switch used to control elevator trim. No other controls were used or required for the experiment

The first experimental instrument suite included the control group instruments listed above with the addition of a track symbol to the HSI. This additional symbol provided the pilot with an indication of instantaneous track (path flown over the ground) allowing the pilots to compensate for the effects of crosswind on approach. Regardless of airplane heading and wind, the track symbol clearly indicated whether the airplane was correcting to or diverging from the localizer (note that we will refer to the straight in approach path as the localizer in this paper, although clearly these displays would work with any high precision positioning system, e.g. ILS with an inertial navigation system, differential GPS, etc.).

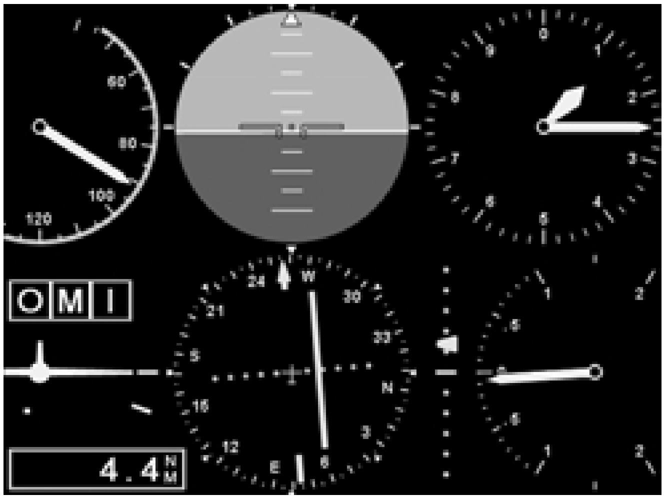

Figure 1. Conventional instrument suite used for control case

The second experimental instrument suite included the control group instruments, the track symbol on the HSI as described above, and an additional symbol called a "glideslope predictor." This symbol, placed adjacent to the glideslope deviation indicator, is simply a instantaneous vertical velocity calibrated with the glideslope intended to provide the pilot with an indication of rate of closure to (or divergence from) the glideslope regardless of current airplane airspeed or wind velocity. The symbol moves up and down like vertical speed, and thus the pilot can control the position of the glideslope predictor by adjusting the airplane's rate of descent. If the glideslope predictor symbol is placed on the same side of the center of the glideslope display as the glideslope indicator, the airplane is correcting to the glideslope. If the glideslope predictor symbol is on the opposite side of the glideslope display as the glideslope indicator, the airplane's deviation from the glideslope is increasing. If the glideslope predictor is placed in line with the center of glideslope display, the airplane is neither converging to or diverging from the glideslope (i.e., if the airplane is two dots low, it will remain two dots low). Pilots were recommended to place and hold the glideslope predictor adjacent to the glideslope indicator to allow the airplane to correct smoothly and exponentially to the glideslope.

The third experimental display was a pathway-in-the-sky concept, as described in the "Background" section above. Our display included an artificial horizon, with hoops depicting a "tunnel" defining the boundary of the horizontal and vertical pathway leading to the runway. By flying through the tunnel, the airplane is kept on the localizer and glideslope. An instantaneous predictor symbol and "corner tick marks" (Regal and Whittington, 1995) were provided to assist the pilot in remaining in the center of the tunnel. Digital airspeed, digital altitude, digital heading, DME, and marker beacons were superimposed on the display. Note that the Stanford tunnel display normally includes indications of raw deviation from horizontal and vertical path; these indications were removed during this study to test the capabilities of the tunnel by itself.

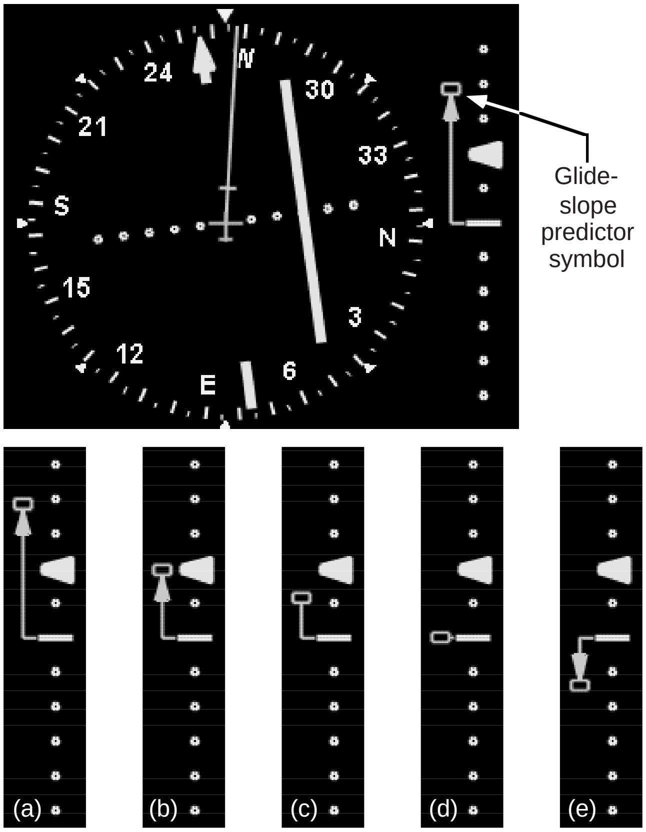

Figure 2. Glideslope predictor symbol adjacent to the glideslope deviation scale, shown in the top panel. In all five cases shown, the airplane is two dots low. (a) The airplane is correcting rapidly to the glideslope (b) The airplane is correcting smoothly to the glideslope (c) The airplane is correcting slowly to the glideslope (d) The airplane is not correcting to the glideslope and will remain two dots low as long as the glideslope predictor symbol is neutral as shown (e) The airplane is diverging from the glideslope.

For the secondary workload task, the pilot controlled a push-button on the yoke. The workload task indicator used here was a sunlight-readable green indicator light placed approximately 5 feet to the left of the flight display (roughly at the edge of the test subjects' peripheral field of view). The workload light was alternately illuminated for a random period of 1 to 4 seconds, then turned of for a random period of 1 to 4 seconds. The pilots were then allowed to fly four more practice approaches, each approach with each of the control and experimental display concepts, while simultaneously conducting the secondary task as much as possible

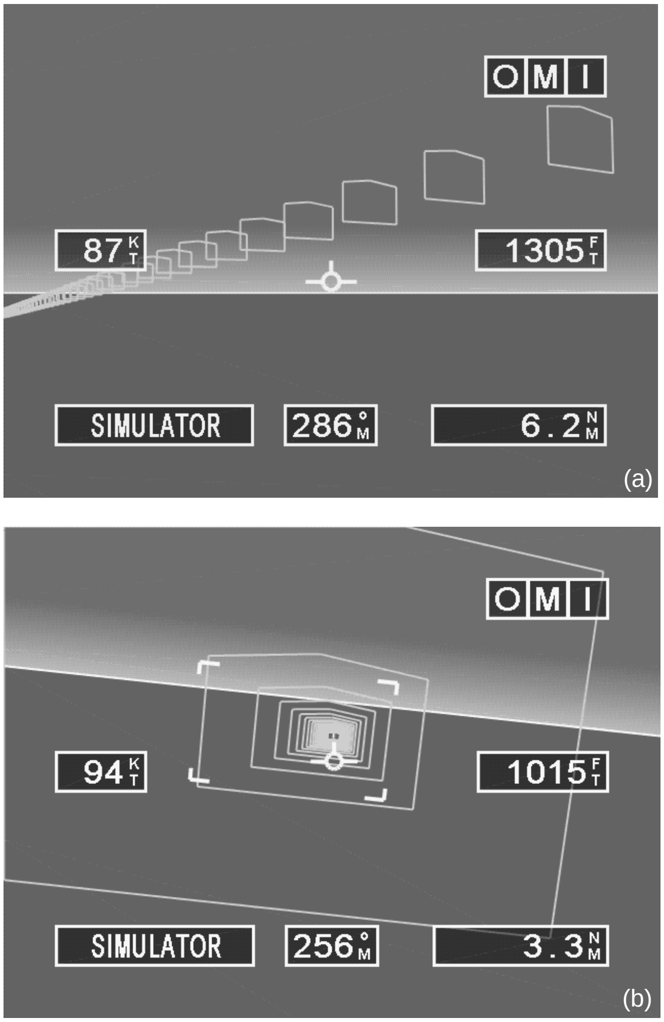

Figure 3. (a) Airplane on intercept to final approach (b) Airplane on final approach inside tunnel.

Subjects. Eight pilot subjects participated in this study. The total flight time for each subject varied between 270 and 3300 hours; the mean total flight time was approximately 800 hours. Each subject was instrument rated; three were certified instrument instructors. All were familiar with the operation of an HSI, and 7 of the 8 had flown an airplane equipped with one. None had experience with the apparatus used or the experimental flight instruments. Each subject flew each of the four control and experimental display concepts six times (for a total of 24 approaches) each time flight straight-in, "ILS-like" approaches.

Results. On average, pilots performed better with each incremental addition to the display suite. Horizontal and vertical rms deviation errors decreased and workload score (0-100, with a higher score denoting better performance on the workload task and an easier display to fly) increased for the track symbol case as compared to the conventional instruments case; the track and glideslope predictor case was, in the same manner, better than the track case; and the pathway-in-the-sky case was better than the track and glideslope predictor case. In particular, the horizontal rms errors and vertical rms errors for the pathway-in-the-sky display were significantly lower than for all the other cases, and the mean workload score for the pathway-in-the-sky display was significantly higher than for the conventional instrument suite case.

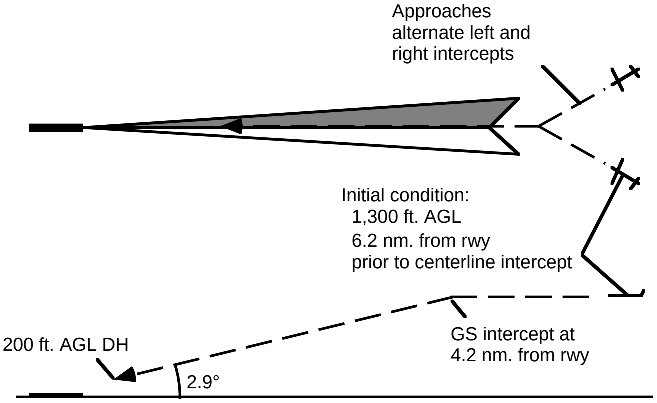

Figure 4. Initial conditions for all simulator test approaches.

These results apply to flying straight in approaches. Other studies (Regal and Whittington, 1995; Knox, 1993; Parrish, et. al. 1994; Reising, et. al., 1995) suggest that pathway-in-the-sky results in improved precision and lower pilot workload as compared to conventional instrumentation for curved approaches as well.

FLIGHT STUDY

An objective of the GPS research program conducted at Stanford University is to demonstrate technologies and identify and address operational issues through inflight testing of differential GPS systems and display concepts. Most previous work on pathway-in-the-sky has been done in simulation due to the high costs of flight test. In our work we attempted to keep equipment costs down not only to reduce the expense of flight test but also to validate the operability of these systems using relatively low cost technology.

The goal of the flight tests was to verify the operability of the flight test equipment in our new flight test airplane, to collect data on the accuracy and precision of the Stanford WAAS positioning system inflight, and to demonstrate the pathway-in-the-sky display inflight through flying curved flight paths and curved precision approaches.

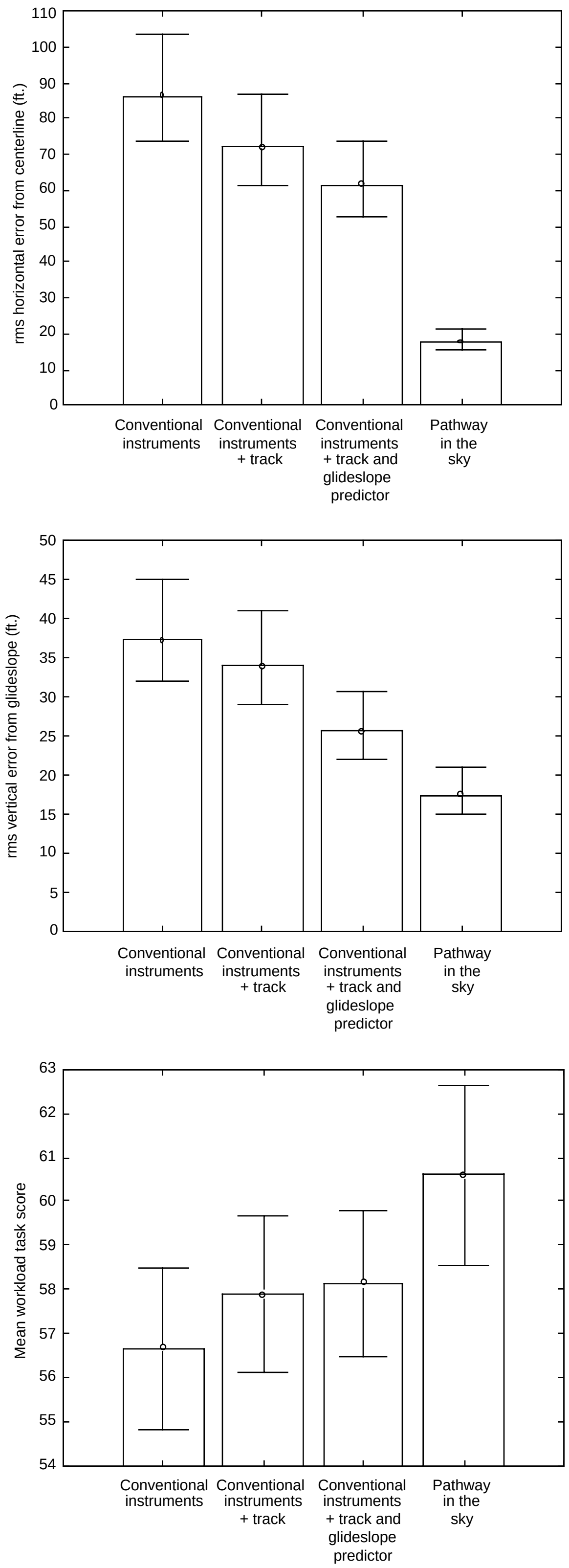

Figure 5. Root mean squared errors and mean workload scores for all cases. Error bars represent 90% confidence intervals.

Equipment. Flight tests were conducted on board a 1965 Beechcraft Queen Air. The twin piston engine aircraft had a large cabin capable of holding two racks of equipment, two pilots, and four flight test engineers or observers. Two pilots shared the flying duties: with approximately 3000 and 15,000 hours of flight time.

Stanford's Wide Area Augmentation System (WAAS) test system using the National Satellite Test Bed (NSTB) reference stations (Tsai, et. al., 1995; Enge, 1996) provided positioning information for the airplane. It provides 2 m 95% vertical accuracy, enabling scenes reconstructed from a 3-D database to very closely match the actual view out the cockpit window. Raw GPS information was acquired through the use of an NovAtel receiver on board the airplane. Differential corrections from the Stanford WAAS system were sent from a ground station at Moffett Field to the airplane using Pacific Crest RFM96 VHF radio modems.

Attitude for the pathway-in-the-sky display was provided by the gyro-augmented short baseline GPS attitude system described in (Hayward, et. al., 1997). This system provided robust high bandwidth attitude information accurate to less than 1 degree in pitch, roll, and yaw.

The 3-D scene was presented on a 640x480 pixel 6.4 inch diagonal active-matrix liquid crystal display (AMLCD) mounted in the pilot’s instrument panel. The upper-right corner of the display is positioned in what is normally the turn coordinator location. Availability of reasonably-priced flat panel displays has traditionally been a barrier to putting computer displays in light aircraft. Fortunately, the growing popularity of laptop computers is now rapidly bringing down the price of AMLCDs and has enabled the first generation of cockpit computer systems with sunlight-readable displays. The display was driven by a ruggedized 90 MHz Pentium personal computer with a 64-bit graphics accelerator card.

The tunnel display was kept simple to minimize computational requirements and enhance ease of use. The field of view represented was 40 degrees vertical by 50 degrees horizontal and included the runway and control tower depicted in correct perspective. The approach and missed approach paths were depicted as “hoops” 100m wide with a spacing of 500m on straight segments. On curving segments the spacing was reduced to 200m to allow the pilot to better see the tunnel, which curved out the side of the display when the aircraft was in a turn. Based on some of our initial flight experience, the sky and ground were darkened and the pathway hoops were lightened for inflight readability. In addition, the predictor was made larger and haloed for improved visibility.

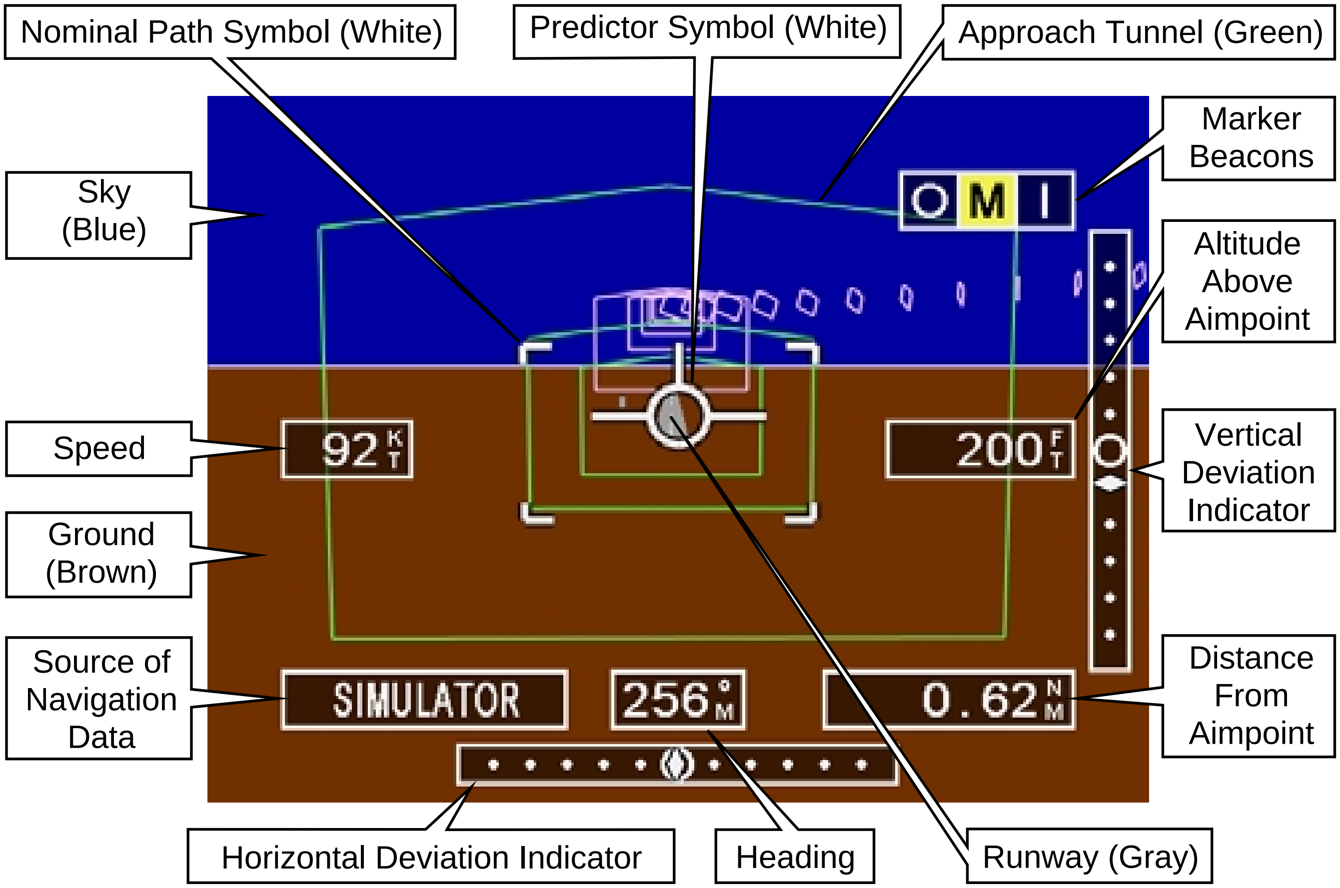

Figure 6. Pathway-in-the-sky display used for inflight testing.

Flight Tests and Results. Once all components of the flight test system were verified as operable, several flights were conducted to demonstrate the capabilities of the pathway-in-the-sky display. Initially, wide patterns were flown with a series of straight (descending) paths leading from an extended base leg to approximately a 2 naut. mi. final approach. Once these demonstrations were successfully completed, similar approaches were flown with curved turns from base to final. Unfortunately, due to traffic constraints imposed by Air Traffic Control during the approaches, the two curved approaches were not completed as planned. However, the smooth, accurate, and (according to the pilot) easy reacquisitions of the pathway after deviation are notable. One of these deviations was actually a left 360 [deg] turn with reference to instruments! Such a maneuver would never be attempted using conventional procedures and technology.

Based on the initial flight trials, new pathways were developed to allow the pilot to fly traffic patterns with a 180 degree turn directly from the downwind leg to a 1 naut. mi. final approach. Traffic patterns were flown to both the left and right runways at Moffett Field. Tight traffic patterns with a landing threshold displaced by 0.75 naut. mi. were also flown to the right runway for maximum noise abatement (it has been suggested that we received noise complaints while flying approaches because by using WAAS positioning we were inadvertently flying over the exact same spot during each approach!). It should be noted that through the use of

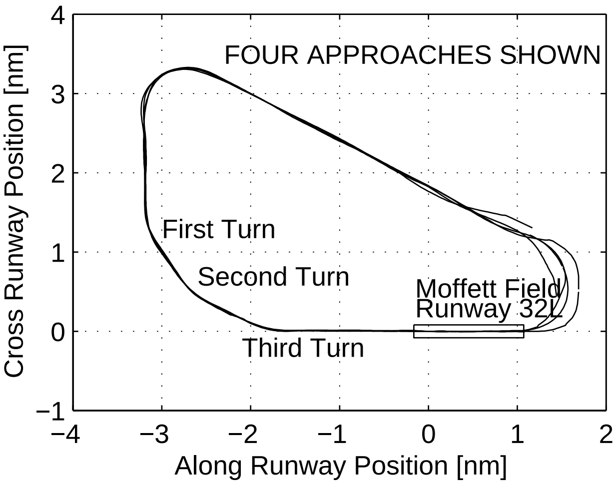

Figure 7. Segmented approaches into Moffett Field.

WAAS and the pathway-in-the-sky system, the flight test airplane was able to fly a close-in traffic pattern (a maneuver normally only done by aircraft flying with visual references) by reference to instruments only.

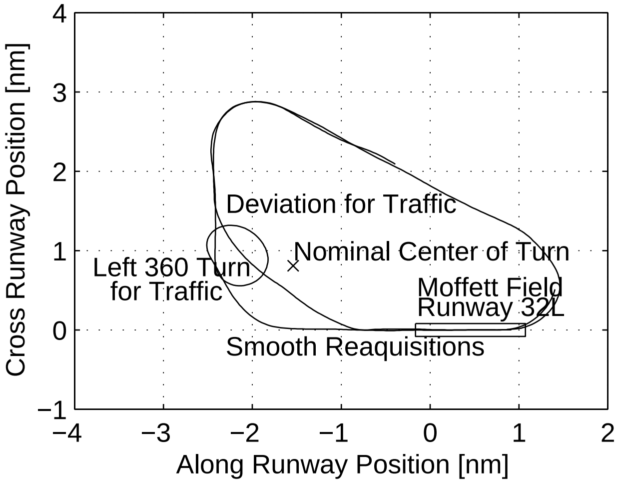

Figure 8. Curved approaches into Moffett Field

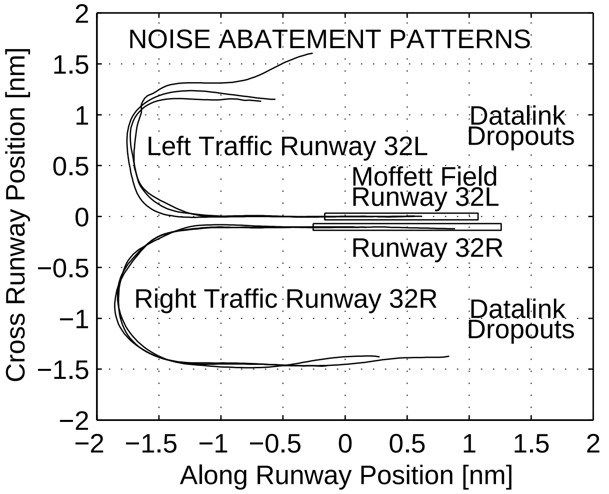

Figure 9. Traffic pattern approaches.

For the segmented approaches, flight technical errors (FTE) were 52.7 ft. (rms) horizontally and 50.7 ft. (rms) vertically. However, note that for the series of approaches included in this measurement the pilot was not asked to attempt to fly the approaches as close as possible to the center of the tunnel (unlike the simulator studies above). It is presumed that improvement in the FTE may be possible if the pilot attempts to null airplane errors from the center of the tunnel.

Flight test demonstrations also showed that very complicated paths may be flown using the pathway-in-the-sky system. Airplane position from a "skywriting" application is shown below. Due to the distance to the datalink transmit antenna, several datalink outages were experienced during the approximately fifteen minutes required to fly the complete pathway. Even so, the results are promising, and suggest that the pathway-in-the-sky system may have applications beyond flying approaches.

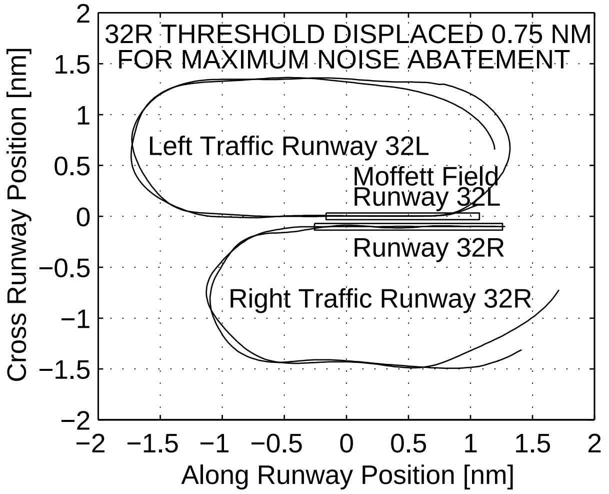

Figure 10. Modified traffic pattern approaches for maximum noise abatement.

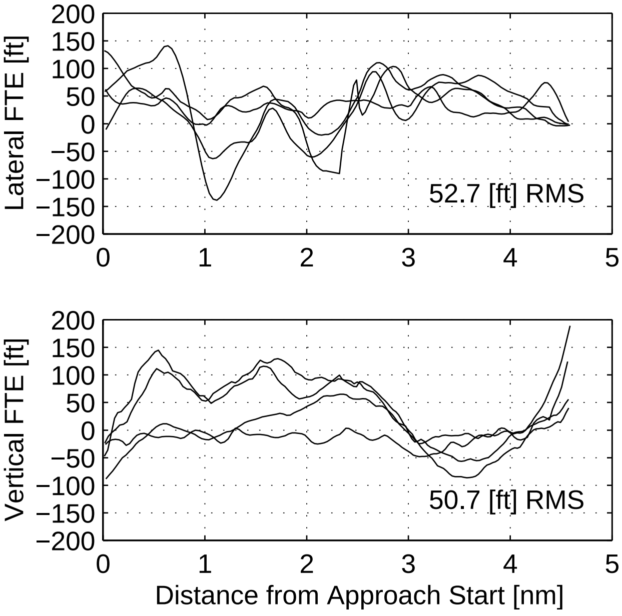

Figure 11. Horizontal and vertical deviations from centerline of pathway for segmented approaches.

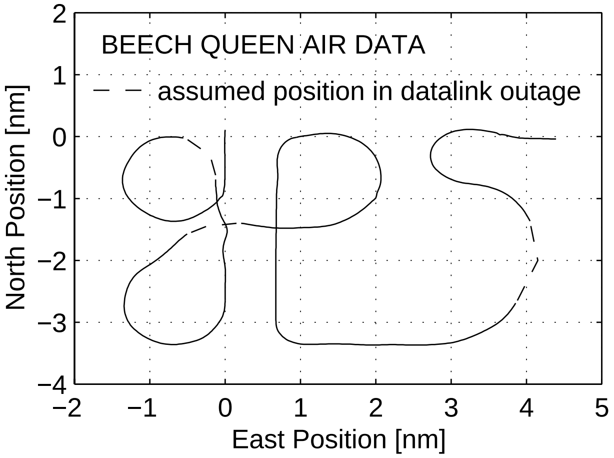

Figure 12. A complex flight path flown at 5,500 ft. MSL north of Santa Cruz, CA.

RESULTS

The results of piloted simulation and flight testing may be summarized as follows:

1. The tunnel display was demonstrated in piloted simulation to have significant advantages over conventional aircraft instrumentation. In particular, flying with the tunnel display results in significant improvements in horizontal and vertical flight precision and in workload reduction as compared to conventional instrumentation
2. The test pilots were able to quickly learn to use the tunnel display to fly complex flight trajectories by instrument reference.
3. The tunnel display allowed repeatable ground tracks even in the presence of varying wind conditions.
4. The pilots were able to make tactical deviations (e.g. in responce to other traffic) and smoothly rejoin the desired path with good situatioonal awaremess.
5. The flexibility of the display enabled rapid development of new procedures in response to noise abatement concerns.
6. The display was demonstrated to provide “skywriting” guidance along a very complicated path. Such guidance is expected to be of value for remote sensing applications.

These results show that a GPS-based tunnel display can make flying along straight and curving flight paths easier and safer. This will be essential in future air traffic environments and is expected to pay additional benefits in specialized applications such as aerial fire fighting, agriculture, search and rescue, military operations, flight test, photogrammetry, and medical evacuation.

CONCLUSIONS

It is the integration of several technologies that sets the tunnel display apart from current display systems; without any one piece of the integrated system the drastically improved display would not be possible. The combination of accurate, low cost position, velocity, and attitude information with advanced cockpit display technology allows for a real time display system significantly better than existing cockpit technology.

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