# Flight Tests of a 3-D Perspective-View Glass-Cockpit Display for General Aviation Using GPS

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## BIOGRAPHIES

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## ABSTRACT

A display that takes advantage of the three-dimensional positioning data available from differential GPS has been flight tested on a general aviation aircraft. This glass-cockpit instrument provides a natural, “out the window” view of the world, making the horizon, runway, and desired flight path visible to the pilot in instrument flight conditions. The flight path is depicted as a series of symbols through which the pilot flies the airplane. Altitude, heading, and airspeed are presented along with lateral and vertical glidepath deviations. Particular attention was given to demonstrating a system satisfying the budget, power, and form-factor constraints of light aircraft.

Simulator tests and flight trials on a Piper Dakota aircraft showed that the tunnel display allows the pilot to hand fly straight-in approaches with equivalent or better flight technical error than with a typical Instrument Landing System (ILS) needle display. Additionally, the tunnel display provides lateral and vertical guidance on curving missed approach procedures, for which ILS cannot provide positive course guidance. The results demonstrate that GPS-based displays can improve navigation along straight and curving flight paths in light aircraft by enhancing pilot situational awareness. Better path-following accuracy will benefit future Air Traffic Control schemes and a variety of specialized applications.

## INTRODUCTION

Today's light aircraft typically fly with cockpit display technology that is 50 years old, in the form of a loosely-integrated set of dials, gauges, and indicators. New opportunities for making flying safer and easier are offered by the accurate 3-D positioning (down to meter and even centimeter accuracy levels) possible with differential GPS. However, even the most accurate information is of no use without a means of displaying it to the pilot. To date, GPS-derived positioning data has typically been displayed in conventional bearing/distance formats, or at best with a small moving map. In this sense, *commercial avionics have barely begun to take advantage of the full 3-D positioning capability offered by GPS.*

To address this need, a display was developed that allows the pilot of a light aircraft to see a three-dimensional (3-D) picture of the outside world, including the desired flight path and runway environment, even in low visibility conditions. This display has been tested in piloted simulations and flight trials, and offers significant benefits over conventional displays.

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## BACKGROUND

### Instrument Landing System

Most light aircraft equipped for instrument flying carry an Instrument Landing System (ILS) receiver and display. The ILS is the most accurate landing system normally used in light aircraft and permits approaches down to decision heights of as little as 200 ft above the runway before the pilot must see the ground or abort the approach [1]. The ILS display shown in Figure 1 consists of two needles that indicate lateral and vertical angular deviations from the straight-in approach path (normally having a slope of 3 deg) down to the runway. If the aircraft is significantly off the glidepath, one or both of the needles will "peg" at full deflection at the edge of the display. Beyond this point, the ILS provides no indication of the magnitude of the lateral or vertical deviation. A significant amount of training and skill is required to smoothly fly an ILS approach by hand. The pilot must integrate information from many sources (artificial horizon, airspeed indicator, altimeter, vertical speed indicator, ILS needles) and mentally differentiate the ILS signal to derive phase lead for the desired damped behavior.

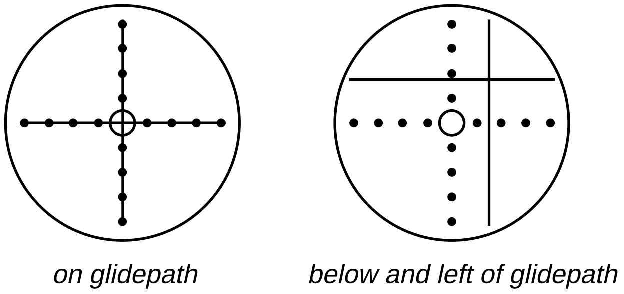
*on glidepath* *below and left of glidepath*

**Figure 1: ILS Needle Display**

If the pilot cannot see the runway at the decision height or if the approach must be terminated for any other reason, a missed approach is executed. This procedure is designed to maneuver the aircraft back into position to make another approach and therefore typically includes curving segments. Because the missed approach leads the aircraft away from the straight-in approach path, the ILS is of no use during this procedure. *The pilot without positive course guidance during one of the most critical phases of the flight.* Due to varying aircraft performance, pilot performance, and wind conditions, large obstacle-free areas must exist around the approach and missed approach paths [2]. Local terrain determines how much clearance is available, which influences the minimum decision height. This ultimately limits the utility of the instrument approach.

The limitations of the ILS and its cockpit display may be summarized as follows:

1. A high level of pilot skill is required to fly an ILS approach smoothly.

2. The ILS only provides a straight-in approach to a runway. Curving approaches are not possible.

3. If the aircraft is not near the desired glidepath, the ILS needle indicator yields only very coarse information as to where the pilot should fly.

4. The missed approach segment of the ILS approach normally has no positive course guidance.

These characteristics all contribute to a more fundamental problem: that *it is easy to lose situational awareness when using an ILS needle indicator*. Unless the aircraft is already nearly on course, it is very difficult to tell from instrument indications where the desired flight path is and how to maneuver to get there. Situational awareness is critical in a demanding phase of flight such as instrument approach, motivating the need for better display technologies.

### Tunnel-in-the-Sky

The problems associated with conventional displays has led to work on displays to provide pilots with increased situational awareness. Since flight fundamentally takes place in three dimensions, much of this work has centered on providing a 3-D perspective view of the outside world. Integrating this 3-D view with the many data sources needed for flight results in a single display from which the pilot can obtain all primary flight data. Enhanced vision systems augment the outside view with this 3-D information using a head-up display (HUD) [3]. A common goal of all systems to date has been to give the pilot a natural representation of the outside world.

A logical extension to the perspective-view display concept is an intuitive depiction of the desired flight path. Previous work has used analogies to roads and tunnels familiar to motorists and has used such terminology as "highway-in-the-sky", "pathway-in-the-sky", and "tunnel" [3-5]. With this scheme, the desired flight path is depicted as a tunnel or series of symbols for the aircraft to fly through. The intent is to inform the pilot where the aircraft is relative to the desired flight path and what action needs to be taken to stay on this trajectory.

Most of the work on 3-D perspective displays has centered on laboratory simulation involving large aircraft models [5, 7]. Most previous work has also focused on HUD technology. However, a computer screen in the instrument panel is a more likely candidate for implementation of a perspective display in light aircraft due to the expense and installation requirements of a HUD. The transition from instrument references to visual references may or may not be complicated by using a perspective display in the instrument panel instead of a HUD. These factors indicate a need for flight testing to assess operational issues involved with perspective displays, especially those related to general aviation.

## SYSTEM DESCRIPTION

To satisfy this flight test requirement, a tunnel display system was developed that addresses the budget, power, and form-factor constraints of light aircraft. This was made possible by a number of enabling technologies that could make a production system possible at the low prices demanded by general aviation. Several of these are outlined here.

### Enabling Technologies

The advent of the Global Positioning System has made accurate 3-D worldwide navigation data available in light aircraft for the first time. With differential GPS techniques, accuracy can be brought down to meter or even centimeter levels while providing the integrity needed for critical flight operations such as precision approach. Accuracy is good enough that a scene reconstructed from a 3-D database very closely matches the actual view out the cockpit window.

As the personal computer has become a commodity product, prices have dropped and computational power has increased. The personal computer is finding increasing use in embedded and industrial applications and is now available in ruggedized and low-power versions. The rising floating-point math performance of new microprocessors allows these devices to perform the computationally-intensive graphics functions available only in expensive workstations a few years ago. A new generation of rendering chips, developed for the mass multimedia and game-player markets, are making sophisticated 3-D graphics possible at favorable price/performance levels.

Active-matrix liquid crystal display (AMLCD) screens are the leading choice for cockpit computer screens. Without modification, consumer displays are not suitable for use in aircraft due to sunlight-readability considerations. Temperature variations at the surface of the display can also render them unusable. For these reasons, aviation AMLCDs are typically fitted with backlights and heaters to make them practical as primary flight displays. 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.

### Hardware and Software Setup

System hardware consisted of a ruggedized 90 MHz Pentium personal computer with a 64-bit graphics accelerator card. The computer drove a 320x234 pixel 5.5 inch diagonal AMLCD attached to the instrument panel glareshield. The 3-D graphics rendering functions were based on a low-level library intended for computer game development. The flight hardware communicated through a serial interface with various positioning sources including the Wide Area Differential GPS System [8, 9] and Integrity Beacon Landing System [10], both developed at Stanford University. The display was also interfaced to a simulator for ground-based testing and rapid prototyping.

### Tunnel Display

The tunnel display, shown in Figure 2, was kept simple to minimize computational requirements and enhance ease of use. The background consisted of the ground in brown, the sky in blue, and a white horizon line to provide the information found on a standard artificial horizon. The field of view represented was 40 deg vertical by 50 deg horizontal and included the runway and control tower depicted in correct perspective. (Other features could have been added, such as taxiways, roads, and water, but at some computational expense.) The approach path was depicted as a series of green “hoops” and the missed approach path as a series of magenta hoops whose pentagonal shape gave an up/down cue to the pilot. The hoops were 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. Superimposed on this 3-D scene were a triangular yellow “own aircraft” symbol at the center of the display, as well as speed, heading, and altitude information. Small tapes at the bottom and right of the display presented the same data shown by standard ILS needles. The sensitivity of these tapes was typically 6 deg full-scale laterally and 1.4 deg full-scale vertically. The 3-D scene could be replaced by a full-screen ILS needle display for comparative testing. Views of the 3-D display on final approach and in a climbing right turn are shown in Figures 3 and 4, respectively.

## SIMULATOR TESTS

A high-quality personal IFR procedures simulator was used to evaluate display performance. The simulator ran on an IBM-compatible personal computer and was modified to produce serial output in a packet format identical to that of the GPS equipment used in flight testing. A control yoke and a console with switches and knobs were used to control power, trim, flaps, and landing gear, so that keyboard use was unnecessary. The flight dynamics emulated those of a high-performance single-engine aircraft. The landing gear of the simulator was left down during these tests to closely parallel operation of the fixed-gear Piper Dakota flight test aircraft. Since the runway database used by the simulator was constructed from real-world information in Jeppesen-Sanderson's NavData database, the display looked and functioned exactly as it did in flight using GPS data. The simulator pilot was a 700 hour private pilot with approximately 50 hours flying on instruments.

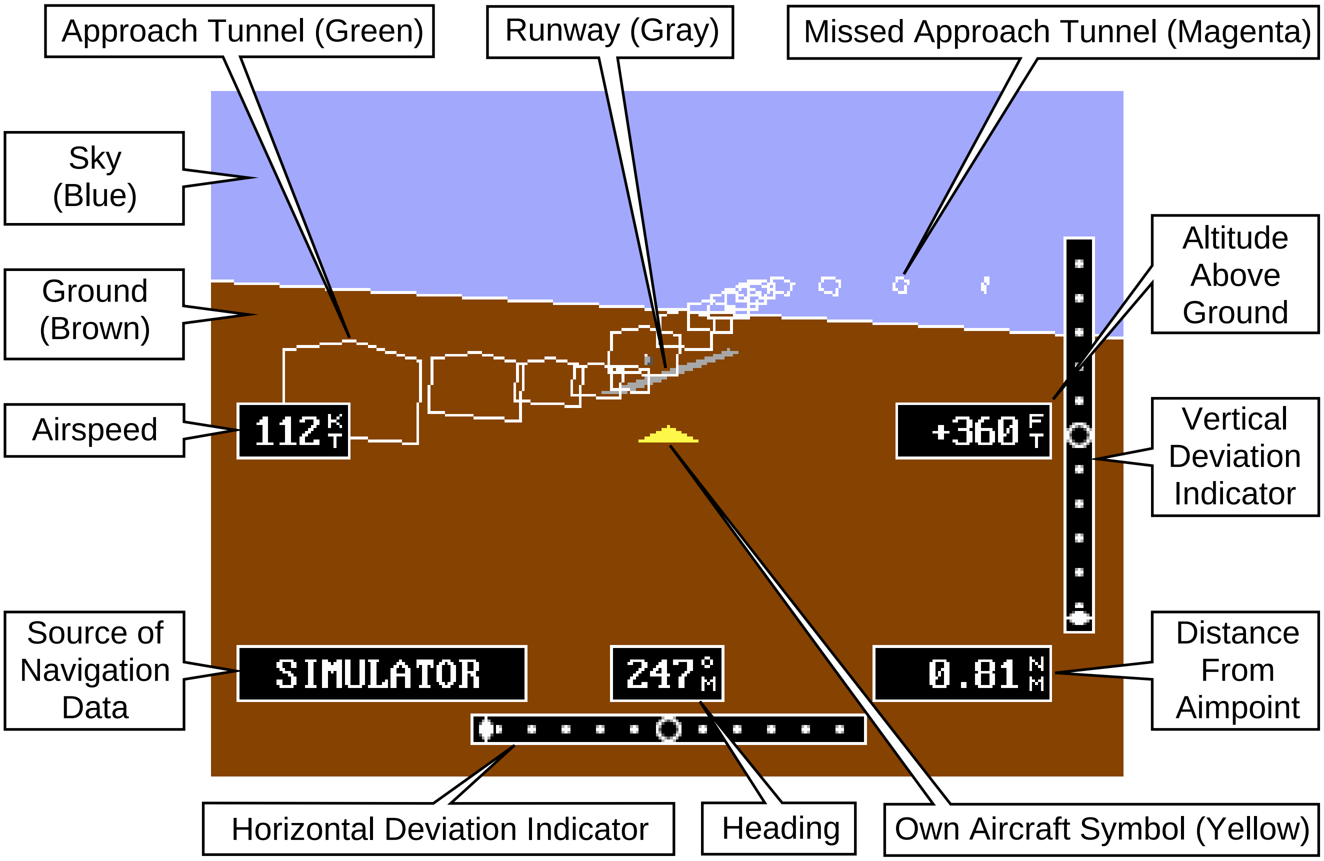

**Figure 2: Tunnel Display**

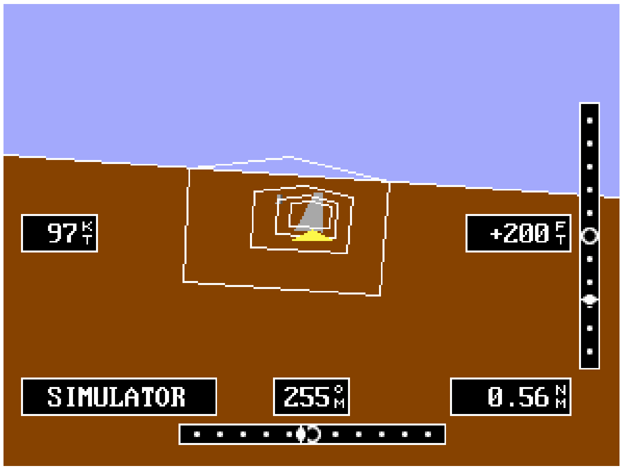

**Figure 3: Tunnel Display on Final Approach**

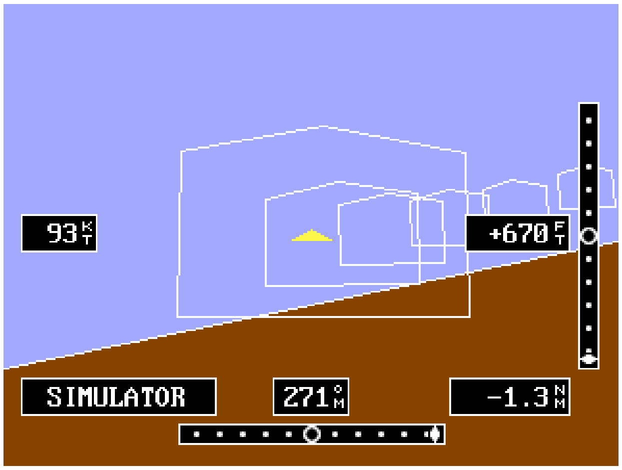

**Figure 4: Tunnel Display in Climbing Turn**

## Procedure

Simulator tests consisted of approach and missed approach procedures for runway 25R at Livermore, California. The pilot flew six runs using the tunnel display and six using the ILS needle display. A "light" turbulence setting was selected and six different wind conditions were used as shown in Table 1. The order of display type and wind condition was randomized to mitigate systematic learning effects. A one-hour training session was given on the use of the simulator and displays.

**Table 1: Wind Conditions for Simulator Tests**

| Wind Direction [deg magnetic] | Wind Speed [knots] | Condition |
|---|---|---|
| 256 | 0 | Calm |
| 166 | 15 | 90° Left Crosswind |
| 211 | 15 | 45° Left Crosswind |
| 256 | 15 | Wind Down Runway |
| 301 | 15 | 45° Right Crosswind |
| 346 | 15 | 90° Right Crosswind |

A bird’s eye view of the procedures conceived for this test is shown in Figure 5. Each run started with the aircraft 11 km from the runway, 2 km to the left of centerline, and below the 2.9 deg glideslope. (This glideslope angle was determined through flight testing at Livermore airport and is expressed relative to local vertical determined from the WGS-84 ellipsoid.) The initial aircraft heading was 285 deg magnetic to make approximately a 30 deg intercept with the runway heading of 256 deg magnetic. The pilot flew straight ahead to intercept the runway centerline and then turned left towards the runway. When the vertical glideslope was intercepted, a descent was commenced to stay on the glideslope. At the decision height of 200 ft above ground level, the pilot was instructed that the runway was not in sight and to execute a missed approach. This consisted of climbing straight ahead to 700 ft, at which point a climbing right turn was initiated. The turn was stopped on a heading of 060 deg magnetic.

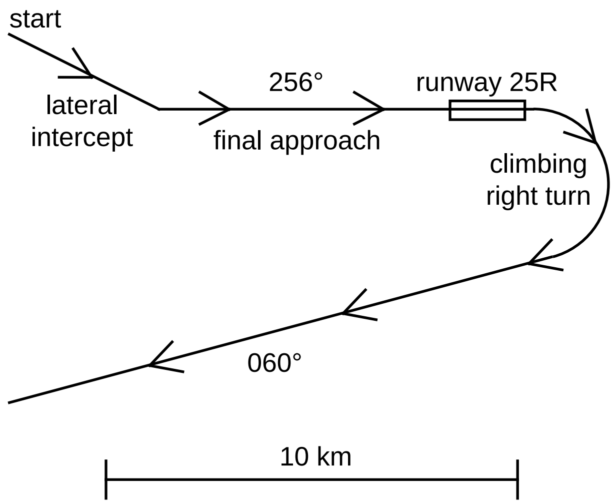

**Figure 5: Bird’s Eye View of Simulator Test Procedure**

## Results

Figure 6 shows vertical flight technical error (FTE: the difference between sensed position and desired position) on the straight-in portion of the twelve approaches from 3.5 nautical miles to 1 nautical mile from touchdown The aircraft moves from left to right on the plot. The tunnel display approaches (represented by solid curves) show generally smaller path following error than the ILS needle display runs (represented by dashed curves). Root-mean-square (RMS) FTE for the tunnel display was 14.2 m compared to 27.5 m for the ILS needle display. At the left side of the plot, the ILS needle runs show a trend towards being low. Since the runs began with the aircraft below the glidepath, this suggests that the pilot was often slow in completing the vertical glideslope intercept.

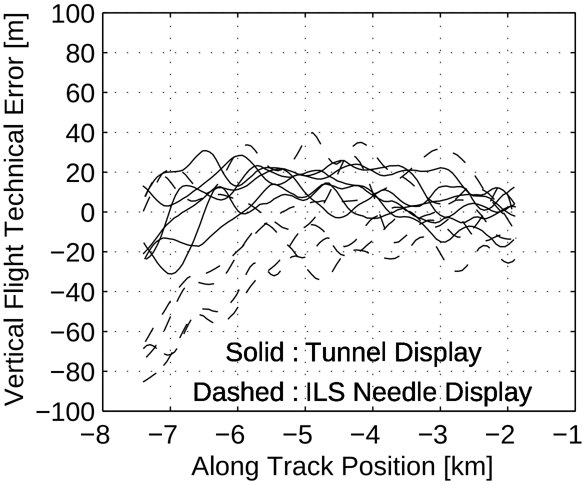

**Figure 6: Simulator Test Vertical FTE**

Lateral or cross track FTE on final approach is presented in Figure 7. Again, the pilot was able to maintain a smaller lateral RMS FTE during the approach. The tunnel runs had an average of 37.1 m RMS FTE compared with 85.9 m RMS FTE for the ILS needle runs. The ILS needle runs exhibit more oscillation or “hunting” for the correct horizontal path, while the tunnel runs seem to be smoother.

Figure 8 shows a bird’s eye view of the lateral intercept made to the runway centerline and reveals some interesting behavior associated with this inbound turn maneuver. The ILS needle runs exhibit overshoot and undershoot as the pilot tried to smoothly intercept the localizer. After intercept, additional hunting for the lateral path is evident. The tunnel runs exhibit less tendency towards overshoot and undershoot, and show that the pilot achieved smoother lateral intercepts when confronted with varying wind conditions.

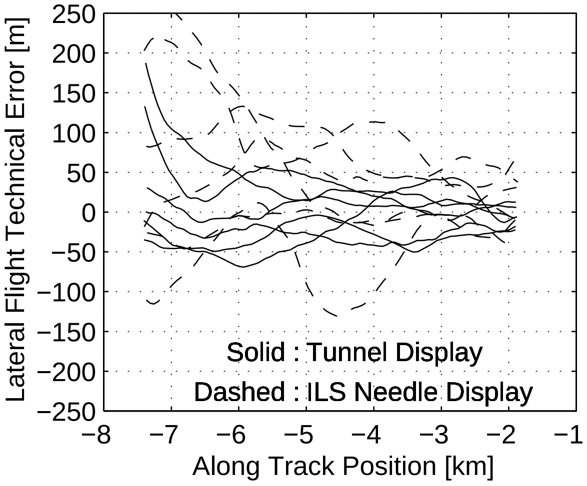

**Figure 7: Simulator Test Lateral FTE**

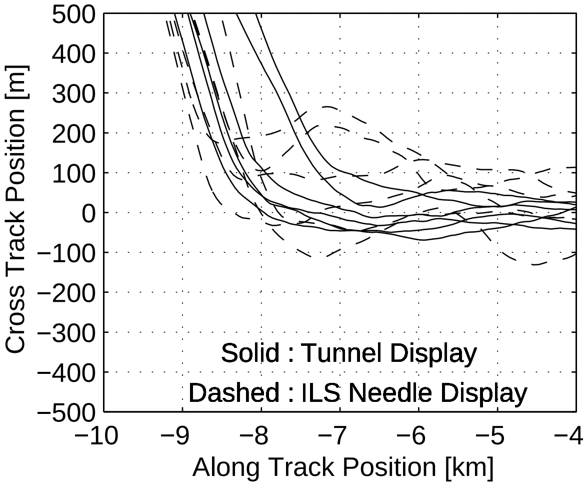

**Figure 8: Simulator Test Lateral Flight Path Intercept**

A bird's eye view of all twelve approaches is shown in Figure 9. On such a large scale, lateral deviations on the approach are difficult to see; however, the missed approach segments look quite different. The curving missed approaches using the tunnel display collapse onto one thick trace, showing that the pilot was able to repeat the curving flight path with each of the varying wind conditions. The missed approaches flown in the conventional manner show scatter due to different wind conditions. Since the pilot consistently ended the right turn at 060 deg magnetic, the varying winds caused different ground tracks for each run. This illustrates the reason for setting aside large obstacle clearance areas when setting up conventional missed approach procedures [2].

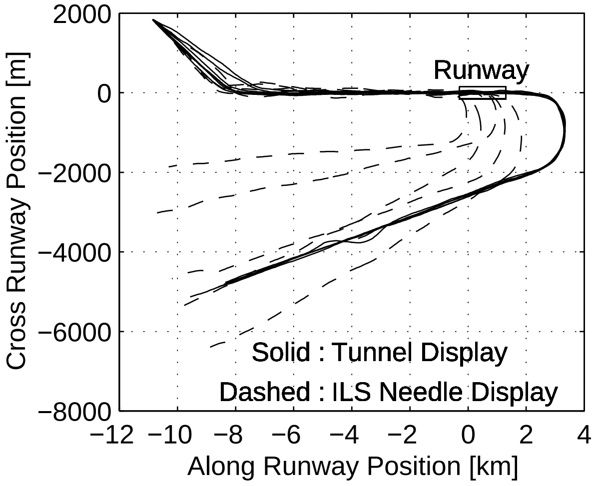

**Figure 9: Simulator Test Bird's Eye View**

### Discussion

On approach, lateral and vertical FTE using the tunnel display were approximately half as large as those using the ILS needle display. When flying with the tunnel display, the pilot commented that he had more difficulty assessing vertical errors than lateral ones. This suggests that a display of raw position error (more prominent than the vertical deviation indicator used) would be desirable.

The tunnel display appeared to allow smoother transitions between flight conditions than the ILS needle display with conventional memorized missed approach instructions. For example, the runway centerline intercept was performed smoothly without overshoot or undershoot. On the curving missed approach, altitude and heading were simultaneously changing, and the pilot was able to easily follow cues on starting and finishing these maneuvers. Climbs and descents were also a good example, where the pilot needed cues on capturing and maintaining an altitude or climb/descent gradient. Of more importance than reducing FTE, it appears that the tunnel display gave the pilot the situational awareness needed to accomplish these tasks accurately and smoothly.

## FLIGHT TESTS

Testing was performed in a four-seat Piper Dakota aircraft as an initial flight evaluation of the system. GPS positioning data was provided by the Stanford Wide Area Differential GPS system and had a 2 m 95% vertical accuracy [9]. The test pilot was the same pilot used for the simulator tests.

### Procedure

Data was taken on straight-in approaches made to runway 25R at Livermore, California. Primary reference to the glidepath was the GPS-based display with both the tunnel and ILS needle formats used. The pilot occasionally looked outside the cockpit to spot nearby aircraft called out by the control tower. A safety pilot flew in the right seat, and all testing was done in visual meteorological conditions. Winds at Livermore during the flight tests were reported as being from 240 deg magnetic at 16 knots.

The aircraft began each approach approximately 10 km from the runway, 3 km to the right of centerline, and 2000 ft above ground level. The pilot then turned onto final approach so as to intercept the 2.9 deg glideslope from below. Upon intercepting the glideslope, the pilot began a descent which continued down to, or slightly below, the decision height of 200 ft. Four approaches are documented here, two flown using the tunnel display and two flown with the ILS needle display.

## Results

Figure 10 shows vertical FTE on the four approaches from left to right. The vertical RMS FTE has the same order of magnitude for both displays (13.2 m for the tunnel display; 19.4 m for the ILS needle display). One of the ILS needle runs exhibits a vertical deviation of more than 50 m above the glideslope.

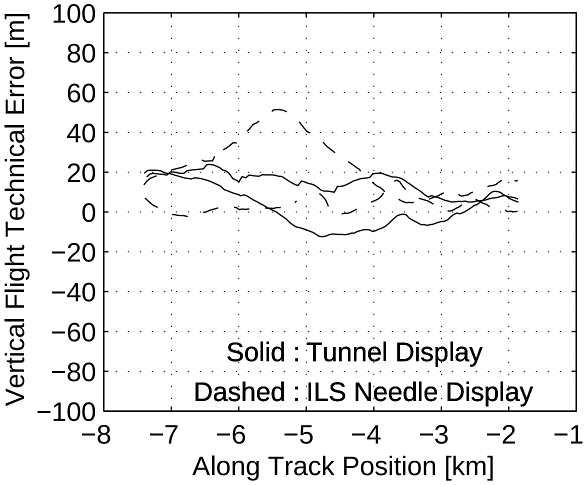

**Figure 10: Flight Test Vertical FTE**

Lateral FTE is shown in Figure 11. These are similar to the vertical FTE plots, and the RMS FTE has a comparable order of magnitude (28.0 m for the tunnel display; 33.0 m for the ILS needle display).

Figure 12 presents a bird's eye view of part of the approach where runway centerline intercepts were completed. One of the ILS needle runs exhibits an overshoot of the runway centerline of almost 0.5 km. This is noted here because of its relatively large magnitude.

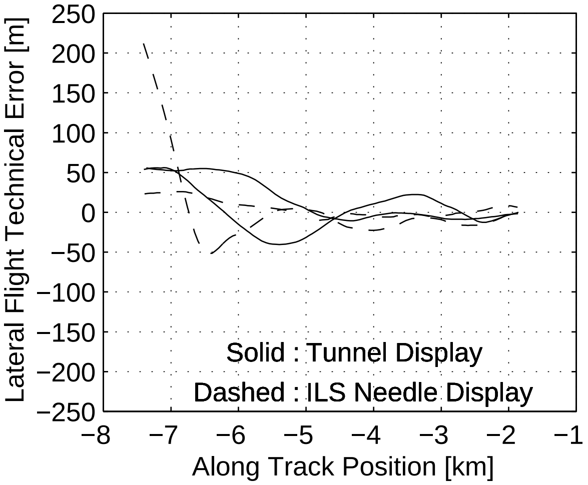

**Figure 11: Flight Test Lateral FTE**

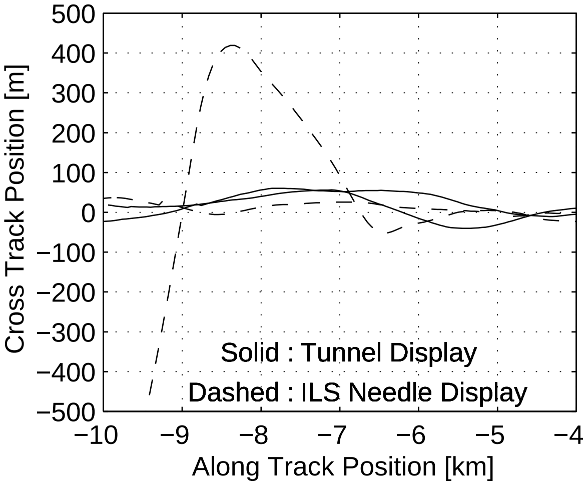

**Figure 12: Flight Test Lateral Flight Path Intercept**

## Discussion

Since there are only two runs per display type, the data is more useful for a qualitative evaluation of the displays than quantitative statistical analysis. The FTE histories do not suggest any reason to believe that path-following performance was markedly different for the two displays. The pilot remarked that vertical deviations were more difficult to assess than lateral ones, a result also seen in the piloted simulations.

It seems that large deviations were more likely to occur with the ILS needle display than with the tunnel display. Examples of this included the vertical FTE deviation and lateral intercept overshoot evident in the data. The tunnel display appeared to allow intuitive recognition of incipient deviations and enabled the pilot to correct for these conditions. As in the simulator tests, the tunnel display enhanced situational awareness during maneuvers with changing flight conditions.

## CONCLUSIONS

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

1. Piloted simulation indicated that the tunnel display could improve FTE over that provided by an ILS needle display on a straight-in approach, while limited flight data suggested that path-following error characteristics were similar for the two displays.
2. The pilot reported that perception and control was most difficult in the vertical dimension, a result which agrees with [5]. Enhanced depiction of vertical error is necessary to give the pilot better vertical control.
3. Experiments showed that lateral and vertical flight path intercepts could be executed more smoothly with the tunnel display than with the ILS needle display.
4. In piloted simulation, the tunnel display allowed repeatable ground tracks on the curving missed approach, even in the presence of varying wind conditions.
5. Large flight path deviations were more easily recognized with the tunnel display, allowing the pilot to make corrections sooner.

In summary, the natural 3-D display format allowed intuitive recognition of the aircraft's relation to the desired flight path. *These results show that the tunnel display can increase pilot situational awareness and make flying safer and easier*.

The piloted simulations and flight tests demonstrate how GPS-based displays can enable accurate navigation along straight and curving flight paths in light aircraft. Greater VFR and IFR path-following accuracy for all classes of aircraft would result in greater utilization and safety in the National Airspace System. Future Air Traffic Management schemes such as the recently-introduced Free Flight concept [11] will most likely demand such improved accuracy. Additionally, the tunnel display has potential benefits in specialized applications such as aerial fire fighting, agriculture, search and rescue, military operations, flight test, photogrammetry, and medical evacuation.

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