Inflight Demonstrations of Curved Approaches and Missed Approaches in Mountainous Terrain

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BIOGRAPHIES

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ABSTRACT

In addition to providing precise and robust 3-D position and velocity information, the Wide Area Augmentation System (WAAS) enables a new class of advanced flight displays that depict realtime "out-the-window"-type scenery even when the aircraft is flying through clouds. Accurate 3-D representation of terrain improves pilot spatial awareness and alerts pilots to the proximity of terrain. Additionally, desired flight path for approach and missed approach can be accurately displayed in the 3-D environment as a "pathway-in-the-sky," a series of hoops through which the pilot flies. Previous simulator and inflight studies have suggested that pilots can fly defined flight trajectories more precisely and with significantly less workload using the pathway-in-the-sky display rather than conventional flight instrumentation. More importantly, 3-D GPS positioning combined with the pathway display allows pilots to fly complex curved approaches and missed approaches that cannot necessarily be flown with current instrumentation. These curved terminal area trajectories could improve flight safety and flexibility through increased terrain separation, flight routing around noise-sensitive areas, lower minimums, etc. Perhaps the most exciting feature of the pathway-in-the-sky display is that it has the potential of being realized with relatively inexpensive LCD technology and attitude systems so as to be affordable to general aviation, business aviation, and regional air carriers.

This paper focuses on inflight evaluations of the pathway-in-the-sky display conducted in southeast Alaska between

Aug. 2 and Aug. 12, 1998, with experienced pilots flying a Beechcraft Queen Air piston twin. GPS position and velocity information for the display were provided by the Stanford WAAS prototype using data from the National Satellite Test Bed (NSTB). Out-the-window video was collected inflight to show how using the pathway symbology facilitates approaches to runways. Complex curved approaches, including approaches turning to a short (less than one mile) final, were flown under simulated instrument conditions. Finally, case demonstrations of curved missed approaches were flown from airports in mountainous terrain.

INTRODUCTION

With the scheduled introduction of the Wide Area Augmentation System (WAAS) as a sole-source precision positioning system only a few years away, it is worthwhile to consider how new flight display technology (i.e., "glass cockpit" technology) in combination with this precision area navigation system might provide novel operational capabilities for all aircraft. In particular, precision instrument approaches are currently designed with long straight-in final approach segments as a result of Instrument Landing System (ILS) technology and using Course Deviation Indicator (CDI) and glideslope needles as the traditional method of displaying error from the desired ILS flight path. While long straight-in final approaches may be acceptable and even optimal at many airports, some airports, particularly those located near mountainous terrain, might benefit from allowing curved paths into and out from the airport. Given that WAAS GPS could provide three dimensional positioning to within a few meters and three dimensional velocity to within a few centimeters per second in the area about any airport in the continental United States and beyond, it is valuable to examine the practicality of flying such curved paths.

In order to demonstrate the viability of flying curved approaches and missed approaches in a ruggedly mountainous environment, the GPS Laboratory at Stanford University conducted a series of flight trials in the vicinity of Juneau, Alaska between August 2 and August 12, 1998. During this period, over 12 individual flight trials and demonstration flights were flown. The details and the results relating to the capabilities of the WAAS system are discussed in *C. Comp, et. al., 1998*. In this paper, we will focus on the display technology and symbology required to manually fly curved flight paths, and the results associated with the flight technical error about the desired trajectories.

BACKGROUND

The concept of the "pathway-in-the-sky" (or "tunnel-in-the-sky") display, in which the desired flight path is presented in 3-D as a series of hoops, goalposts, or a "road" in the sky through or over which the pilot flies to arrive at the desired destination, has been around for decades, and has been studied extensively in simulation in the past 15-20 years (Wiener and Nagel, 1988; Grunwald, 1984). In summary, prior work has shown that the pathway-in-the-sky display provides intuitive guidance information for the pilot, especially when compared to conventional flight instrumentation (Barrows, et. al., 1997). In particular, the pathway-in-the-sky display proves most valuable while manually flying curved flight paths when compared to conventional instrumentation by improving flight positioning precision and reducing pilot workload (Regal and Whittington, 1995). Prior work by Stanford University indicates that that the benefits of the pathway-in-the-sky display shown in simulation are realizable in flight when the display is driven by precise, accurate, and timely position and attitude information (Barrows, et. al. 1996; Barrows, et. al. 1997).

FLIGHT STUDY

In order to demonstrate the potential of using the pathway-in-the-sky concept to fly curved approaches in mountainous terrain in southeast Alaska, the existing Stanford pathway-in-the-sky display was updated by incorporating newer computer hardware and software. This newer equipment enabled an increase in display frame rate from approximately 15 frames per second to 30 frames per second or more. Three dimensional textured terrain was added to the perspective display to improve pilot spatial awareness (see below). Finally, a Matlab™ script was written to aid the rapid manual generation of 3-D flight trajectories which could be loaded by the display software and shown as pathways for the pilot to follow.

Hardware. Flight testing was conducted on board a 1965 Beechcraft Model BE65-A80 Queen Air piston twin engine airplane. The airplane has a large cabin interior capable of holding two full racks of equipment, and multiple GPS antennae installed on the fuselage and wings for test purposes. The airplane, owned and operated by Sky Research, Inc., was always commanded by one of two pilots with significant experience with the Queen Air and other aircraft.

Precision positioning for the flight display was provided by prototype WAAS user equipment developed by the GPS Laboratory at Stanford University (Comp, et. al., 1998). Raw GPS position and velocity measurements were provided at 10 Hz. by a NovAtel GPS card inside the P90 rack-mount personal computer which ran the differential GPS software. Differential corrections for the GPS equipment were generated on a DEC Alpha master station located at Stanford University using information from the FAA National Satellite Test Bed (NSTB) ground reference stations. Corrections were sent to the airplane either via phone line and VHF ground-to-air datalink, or by a geostationary satellite broadcasting correction information on L1. For VHF communication, the experimenters used Pacific Crest RFM96 radio modems. For satellite communication, corrections were received by a NovAtel Millenium GPS unit on board the airplane.

Realtime attitude was provided by a Stanford GPS/inertial system (Hayward, et. al., 1998). Attitude information was provided at approximately 20 Hz.

The flight display was generated by a dedicated Pentium II 333 Mhz. industrial personal computer system driving an Obsidian 2 graphics card manufactured by Quantum3D, Inc. This lower cost graphics system is capable of drawing many thousands of textured polygons per frame while maintaining approximately 30 frames per second or more. All lines on the display, including the pathway, were drawn antialiased, or smoothed. The three dimensional flight display was presented to the pilot on a 6.4 inch diagonal sunlight readable AMLCD display *(Fig. 1).*

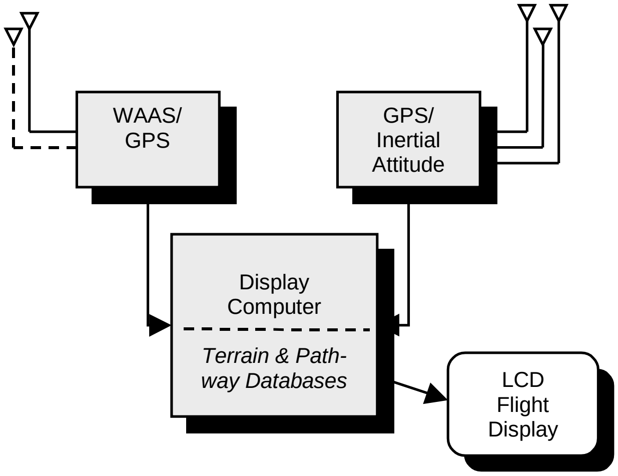

Figure 1. Schematic of equipment used to drive pathway-in-the-sky flight display.

Display Software. Code to generate the 3-D perspective display was written in C; the graphics were driven by a Quantum3D software toolkit called OpenGVS which allows for the realtime presentation of 3-D scenery.

Generating the terrain in the display involved integrating data from two database containing land points and coastline points. The land and coastline databases were obtained from the USGS and the Alaska Department of Natural Resources, respectively. The terrain surface was rendered as a mesh calculated from a Delaunay Triangulation using selected points in each database as nodes. This mesh was then rendered to the user/pilot in OpenGVS.

The volume of raw data would overwhelm the graphics display capability of the display computer if some sensible reduction weren't employed. To reduce the number of data points we discarded points of low curvature and employed the concept of levels of detail. To determine low curvature points the 2-D Laplacian at each Land point and the 1-D Laplacian at each Coastline point were calculated. Empirically determined threshold curvatures determined whether a particular point would be discarded or not. Additional data sets with the thresholds increased were created to generate terrain over the identical area yet with more points discarded. These duplicate data sets with lower resolution are heretoafter referred to as lower levels of detail. Terrain in the background of the display is displayed in the lowest level of detail with increasing detail in the mid- and foreground. Using this method we were able to eliminate over 90% of the land data and 66-75% of the coastline data without visible reductions in the resolution of the

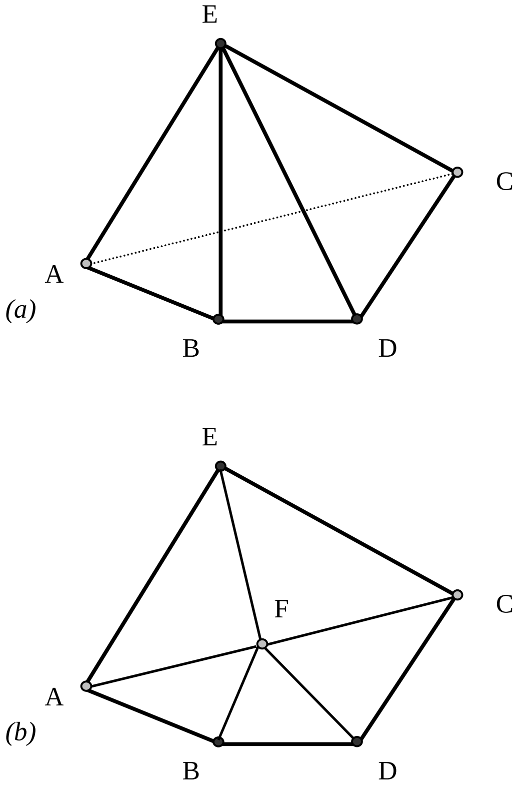

Figure 2. (a) Terrain triangles before coastline points are connected. (b) Triangles after coastline points A and C are connected by adding a new point.

display. This step enabled the display to refresh itself at a rate of 30 Hz or more.

To translate the data from a database to a set of polygons we used a 2-D Delaunay traingulation, using the points in each database as nodes. When adding the coastline precaution had to be taken to ensure that the Delaunay algorithm would connect adjacent coastline points. It is essential that adjacent coastline points are connected by the triangulation. As illustrated in *Fig. 2,* simply adding the coastline points to the land points and triangulating may not connect all the coastline points. In this case points A & C are coastline points and there are two triangle edges crossing AC. To ensure that A and C get connected, the midpoint of AC, F was added to the coastline data and the triangulation was recalculated, and the TIN was checked to make sure that A and F and F and C were connected. In some instances several points had to be added to connect a segment of the coastline. This algorithm is not being presented as optimal; however it worked adequately to the purposes of this effort.

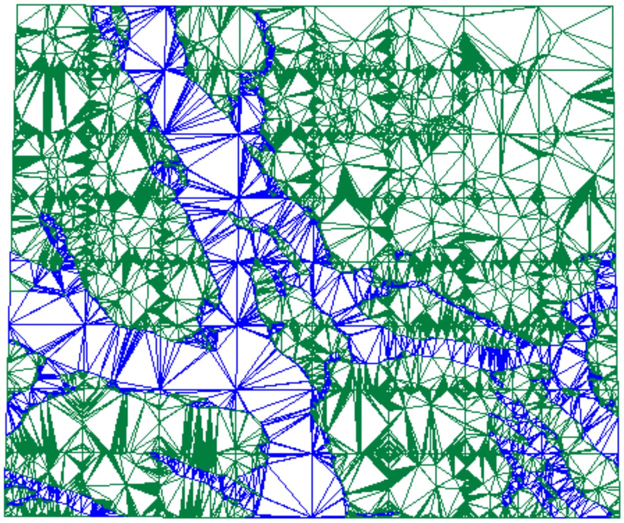

Figure 3. Triangular Irregular Network (TIN) generated about Juneau, AK

With the coastline inserted and connected in the mesh, the triangles within the coastline limits must be identified so that they can be represented as water. A recursive algorithm that ‘walked’ within the coastline, stopping only at the edge of the data set or at the coastline, quickly set a water flag for all the triangles within the coastline. Once this data was processed to create 3-D water and land triangles, the output was sent to a file readable by the display software code to make a ground/water object representing the local terrain *(Fig. 3).*

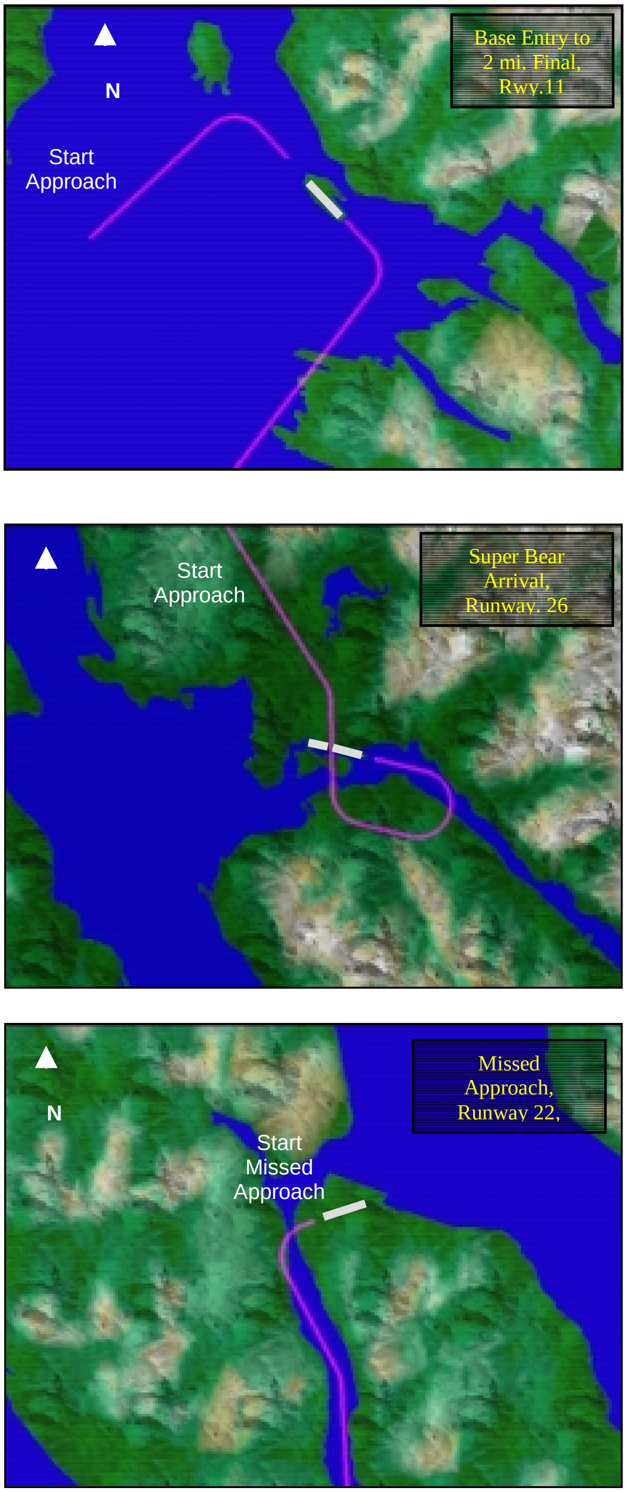

Figure 4. Three of the 38 pathways generated for the Alaska flight tests. The upper map shows an approach into Sitka, AK. The middle map shows a slightly more complicated approach into Juneau, AK. The lower map shows a missed approach from Petersburg, AK, which takes advantage of lower terrain in the Wrangell Narrows south of the airport.

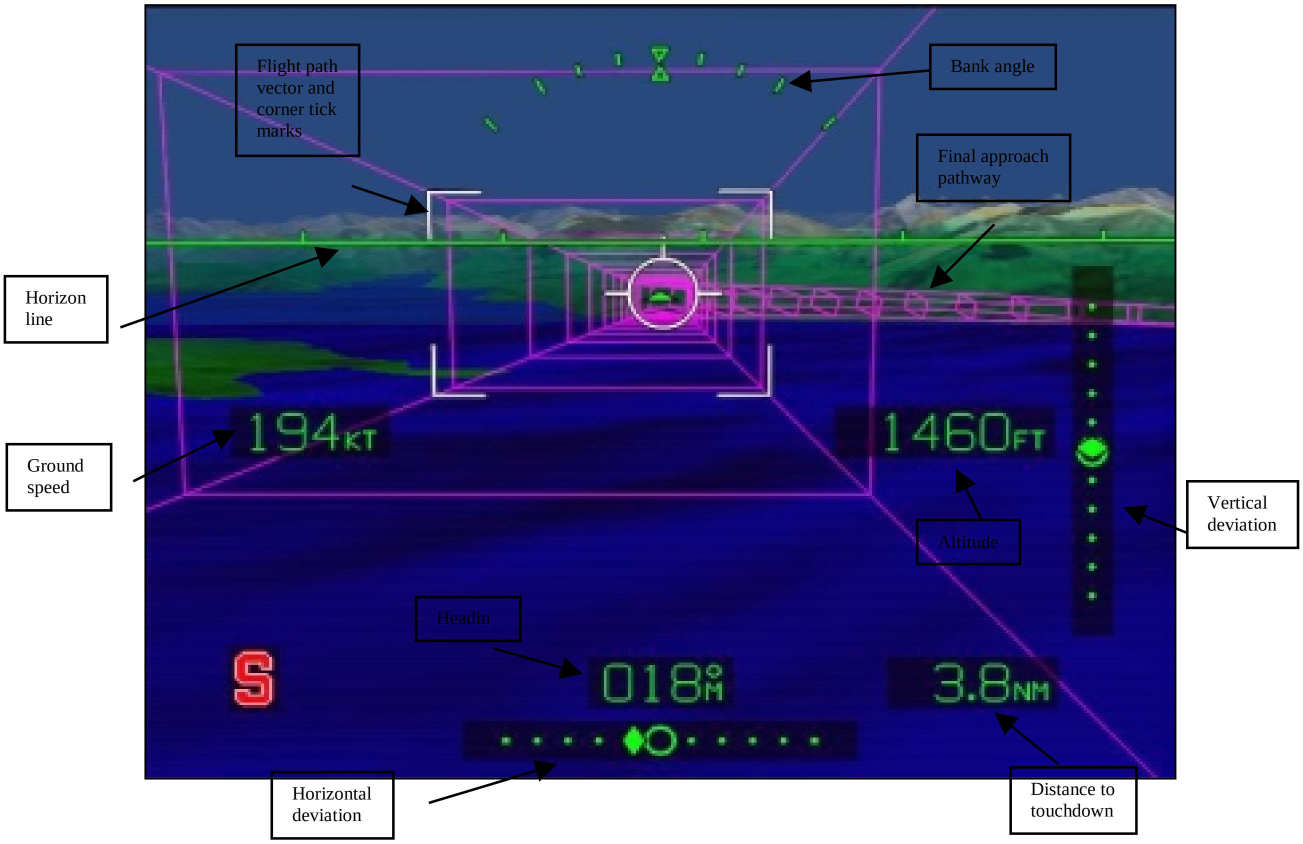

Figure 5. Pathway-in-the-sky/terrain flight display.

Tunnel hoops were drawn 100 meters wide and 60 meters tall, and evenly spaced every 200 meters along the pathway. These values had been shown in prior flight testing to promote small deviations from pathway centerline without requiring strong pilot effort to remain inside the pathway.

Pilots were also provided with supplementary flight information including bank angle, horizon line, groundspeed, altitude, heading, and distance to touchdown point. Current horizontal and vertical deviation from the pathway centerline were also provided in the form of a Course Deviation Indicator (CDI) and a vertical deviation indicator which was, in effect, analogous to a glideslope indicator *(Fig. 5)*.

Pathways Flown. 38 total pathways were programmed for flight in southeast Alaska, with most of these paths (24) for operations around Juneau International Airport. 7 paths were created for operations around Sitka, Alaska; the remaining 7 paths were created for operations around Petersburg, Alaska *(Fig. 4, previous page)*. Programmed pathways included closed traffic patterns, overlays of existing IFR arrivals into Juneau and Sitka, and overlays of certain visual arrival procedures into Juneau. Additionally, pathways included overlays of Alaska Airlines RNP arrivals into Juneau, as well as variants/combinations of approach procedures, such as LDA Runway 8 Circle to Land Runway 26 at Juneau. Completely novel pathways were flown, such as Base Entry to Runway 11 at Sitka and a missed approach path from runway 22 at Petersburg. Pathways were constructed from level, climbing, or descending straight segments and level, climbing, or descending constant radius arcs. Given a 120 knots approach speed, a corresponding arc radius of 1500 meters was selected as easy to fly.

A total of 9 pilots flew the pathway-in-the-sky display from the left pilot seat. Pilot experience ranged from approximately 200 hours to 15,000 hours total time. All pilots were instrument rated. Some pathways were flown with the flying pilot wearing view-limiting goggles designed to simulate flight in instrument meteorological conditions. The right seat of the airplane was always occupied by the pilot-in-command of the aircraft, who verified terrain and traffic separation during the flight trials and was responsible for the overall safety of each flight.

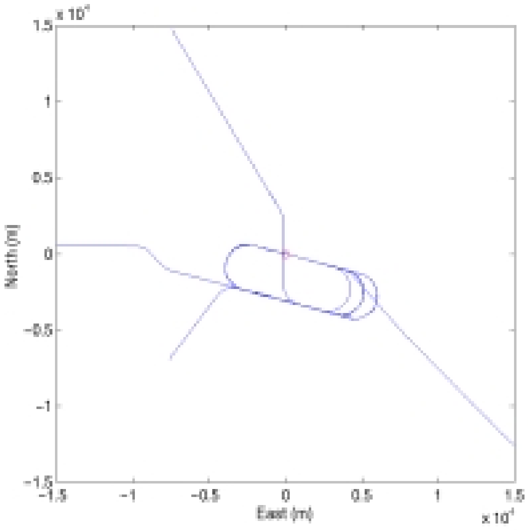

Figure 6. Actual flight position data for selected arrivals to runway 26, Juneau, AK.

RESULTS

During flight trials, the perspective display was operational for 12 hours 55 minutes; of this time, 4 hours 28 minutes were spent flying inside the tunnel (the remainder of the time was, in general, spent repositioning the airplane for additional approaches). A total of 57 paths were flown, of which 47 were approaches to landings, touch-and-goes, or low approaches (overflight of the runway) *(Fig. 6)*. Seven inflight sections were flown; these included partial approaches and racetrack paths. Three missed approaches were flown at Sitka and Petersburg.

Overall, flight technical errors (FTE) were 77 ft. rms horizontally and 36 ft rms vertically *(Fig. 7)*. These very precise FTE's were maintained even though pilots were only instructed to "fly the tunnel." It is presumed that these errors would have been even smaller if the pilots had been instructed to "stay as close to the center of the tunnel as possible." The result that the horizontal errors were over twice the vertical errors can be explained partly by the fact that the tunnel is wider than it is tall; however, further investigation into this anomaly is being conducted.

Most pathways were made up of both curved (constant radius) and straight tunnel segments. Pilots flew a total of 281 segments in the 57 paths flown, or 4.9 segments per tunnel. Of these 281 total segments, 182 were straight and 99 were curved. Measured FTE's are comparable between curved and straight segments, suggesting that (given the turn radius selected) complex approaches can be flown without concern that curved segments might exacerbate errors from pathway centerline *(Fig. 8(a))*.

To check the feasibility of using the pathway-in-the-sky display during instrument meteorological conditions (IMC) (i.e., when in clouds or fog), some approaches (17 of 57) were flown with the pilot wearing a view-limiting device to simulate IMC, and to verify that pilots did not use any external cues to fly which would not be available to the pilot in IMC. Results show that pilots do not fly any less precisely while flying under simulated instrument conditions *(Fig. 8(b))*.

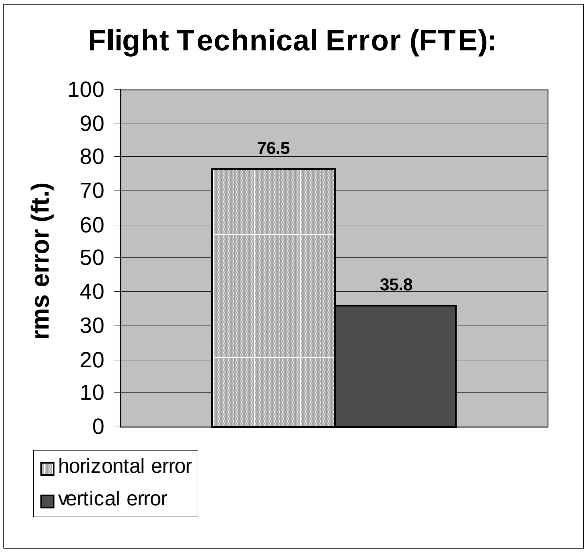

Figure 7. Overall flight technical error for all pathways flown.

CONCLUSIONS

Results suggest that using a perspective pathway-in-the-sky display in conjunction with WAAS position and good attitude information could be an economical solution to flying curved approaches and missed approaches, enabling the advantages and the benefits associated with such flight procedures. Pilots who have flown the display report subjectively that as long as care is taken to make certain that high contrast is maintained between the tunnel and the scenery behind it on the flight display, the pathway-in-the-sky/terrain display is easy to fly and provides valuable information about nearby terrain.

Information displayed on the 3-D pathway-in-the-sky/terrain display provides excellent course guidance and terrain awareness in the area in front of the airplane. This information is clearly tactical in nature, and it should be evident that such a perspective display provides very limited strategic flight information. A perspective display as described in this paper would be well complemented with a map display or other strategic flight display which

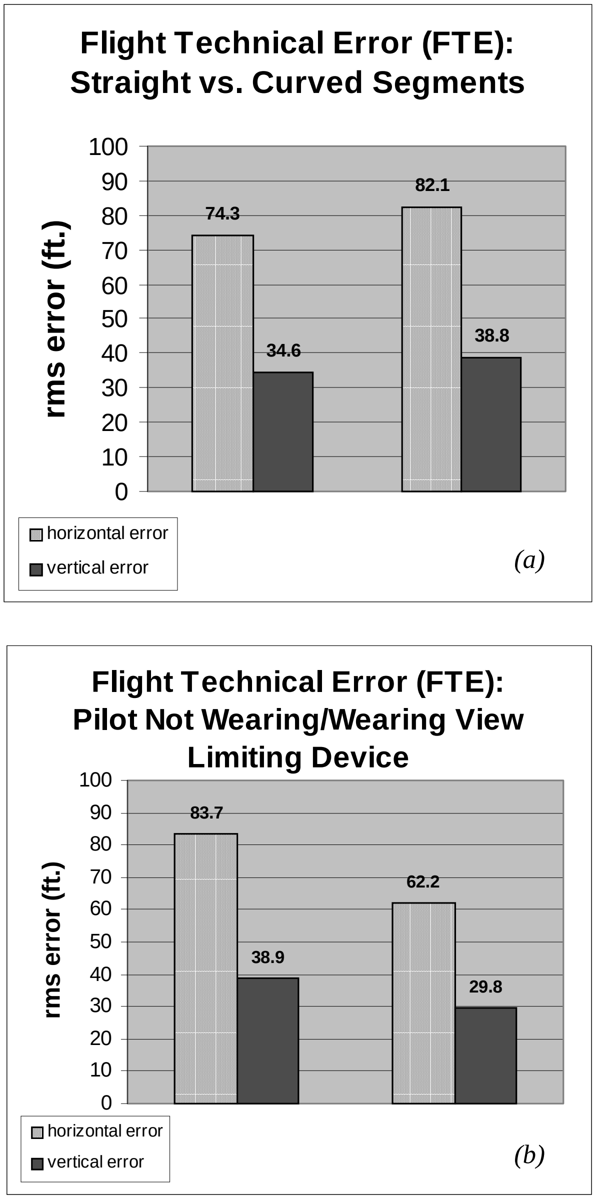

Figure 8. (a) Comparison of FTE between straight and curved segments indicates similar precision. (b) Comparison of FTE between pilot flying in simulated instrument conditions vs. pilot flying in visual conditions suggests that tunnel flying precision is not lost when the pilot cannot see outside the aircraft.

provides intuitive route/navigation information and terrain information 360 degrees about the airplane and about the planned flight path.

It should be noted that while (as noted earlier) there is evidence that the pathway-in-the-sky display allows for precise and easy manual flying of curved flight paths, such a display may not be necessary to fly curved approaches and missed approaches. Autopilots could use WAAS position and velocity to fly curved trajectories; pilots need only the flight information required (such as horizontal and vertical path deviation and a map display) to retain an acceptable level of situational awareness throughout the approach. Alaska Airlines currently flies curved paths into and out from Juneau using a system that requires a combination of GPS, INS, Flight Management System (FMS), a map display, and Enhanced Ground Proximity Warning System (EGPWS).

Nevertheless, the pathway-in-the-sky display seems to demonstrate excellent guidance for flying curved approaches in actual flight conditions, and there may be flight operations or aircraft which are better suited for using this technology to fly manual curved approaches and missed approaches. Continued effort in identifying and solving issues associated with certifying curved approaches and missed approaches and the technology required to fly them should be supported.

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