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Applications of Global Positioning System Velocity-Based Attitude Information

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Applications of aircraft attitude information obtained from single-antenna global positioning system (GPS) receiver measurements are discussed. A recently introduced framework to synthesize attitude information from GPS velocity vector measurements is reviewed. The framework combines the benefits of high-quality GPS velocity measurements with a novel velocity-vector-based flight control paradigm to provide a means for the human operator or autopilot to close the aircraft flight control loop. Three possible applications of this novel concept are discussed. A single-antenna GPS-based backup attitude indicator is evaluated in flight and compared to the traditional attitude indicator. In addition, single-antenna GPS-based autopilot and tunnel-in-the-sky trajectory guidance systems are demonstrated in flight. Unlike traditional attitude indicators and autopilot and trajectory guidance systems, these applications rely solely on the information obtained from a single-antenna GPS receiver. This concept thus has significant system integration and cost advantages and makes a number of glass-cockpit capabilities affordable to the General Aviation aircraft community.

I. Introduction

IN recent years, novel global positioning system (GPS) attitude determination methods have been proposed and successfully tested.[1,2] They rely on the use of multiple antennas, separated by known baselines, to measure the carrier phase differences of the GPS signals between antennas. After resolving the integer ambiguity inherent in the measurements, the attitude can be calculated. Multi-antenna GPS-based attitude determination is a direct measurement of the vehicle attitude and, hence, is not affected by drift problems. Its accuracy is proportional to the inverse of the antenna baseline lengths. Thus, larger baselines reduce the attitude error and, hence, the vehicle dimensions constrain the achievable accuracy. Some of the disadvantages associated with multiantenna GPS-based systems are the extensive antenna installations and baseline calibrations as well as the aircraft specific certification that incur both complexity and cost.

A methodology to synthesize attitude information from GPS velocity measurements has recently been developed.[3,4] It combines the benefits of high-quality velocity measurements with a novel flight control paradigm that controls the aircraft velocity vector directly, rather than indirectly through the control of attitude, as in traditional control schemes. The synthesized attitude information consists of flight-path angle and roll angle about the aircraft velocity vector axis and is termed *pseudoattitude* to distinguish it from traditional attitude consisting of pitch and roll angles about the body axes. Pseudoattitude is inferred from aircraft velocity information, measured by a single-antenna GPS receiver, under the assumption of coordinated flight using a simple point mass aircraft model. The velocity measurements are based on Doppler frequency shift measurements of the GPS receiver carrier tracking loop and are readily obtainable in most GPS receivers.

The availability of affordable GPS velocity-based attitude information creates unique opportunities for new applications. This paper focuses on a number of applications of GPS velocity-based attitude information.

Single-antenna GPS-based attitude information has the potential to greatly increase the integrity of cockpit systems. For instance, its use as a backup attitude indicator for General Aviation (GA) aircraft provides the pilot with an additional level of attitude redundancy. Furthermore, GPS-based pseudoattitude constitutes a source of attitude information that is functionally independent from attitude measured by traditional inertial sensor-based systems and provides, therefore, dissimilar redundancy. This attitude information can be used in fault detection and isolation schemes as tie-breaker or cross reference, thereby greatly increasing cockpit integrity.

With the availability of GPS-based attitude information, a single-antenna GPS receiver can provide all of the information necessary to control and guide an aircraft. Classes of aircraft, such as expendable small unpiloted aerial vehicles (UAV) that recently began to emerge, can be instrumented with a single-antenna GPS receiver as the primary sensor and can be controlled using a single-antenna GPS-based autopilot. This has significant weight, size, power, and cost advantages compared to traditional instrumentation architectures.

Furthermore, the availability of single-antenna GPS-based position, velocity, and flight control information enables the implementation of trajectory guidance systems solely based on GPS information. Guidance systems such as tunnel-in the-sky and flight director displays, which, thus far, have relied on expensive sensor hardware can now be implemented using a single-antenna GPS receiver. This has significant system integration and cost advantages and, consequently, allows the larger GA community to benefit from these systems.

This paper discusses the implementation and flight demonstration of a number of these applications. The following section reviews the synthesis of pseudoattitude from GPS velocity measurements. Sections III–V discuss the implementation of three applications of GPS-based pseudoattitude and present the results of flight-test demonstrations. Section III presents a backup attitude indicator for GA aircraft, Sec. IV discusses an autopilot system, and Sec. V a tunnel-in-the-sky trajectory guidance system, all of which rely entirely on information obtained from a single-antenna GPS receiver. Finally, Sec. VI presents the conclusions.

II. Pseudoattitude Synthesis

Pseudoattitude is inferred from aircraft velocity information, measured by a single antenna GPS receiver, under the assumption of coordinated flight using a simple point mass aircraft model. The assumption of coordinated flight is valid for most flight conditions encountered by conventional aircraft and, thus, does not constitute a significant limitation to this concept. Furthermore, it can be shown that the synthesized attitude information is also useful in the presence of moderate sideslip conditions.[4]

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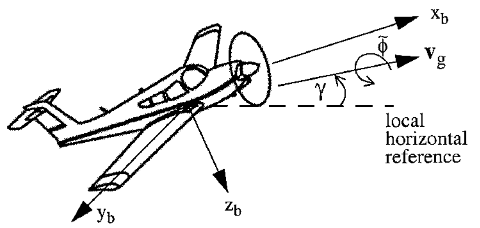


Fig. 1a Illustration of pseudoattitude.

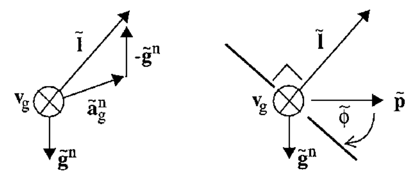


Fig. 1b Determination of pseudoroll.

As stated earlier, attitude information synthesized from the aircraft trajectory has been termed pseudoattitude to distinguish it from traditional attitude consisting of pitch and roll angles. In contrast to traditional attitude, which is referenced to the aircraft body axes, pseudoattitude is referenced to the aircraft velocity vector and consists of flight-path angle γ with respect to the (local horizontal) ground plane, substituting for traditional aircraft pitch angle, and a pseudoroll angle $\tilde{\phi}$ about the aircraft velocity vector axis, substituting for traditional roll angle. The pseudoroll angle is defined as the effective bank angle, which corresponds to the observed lateral rate of change of the velocity vector. Pseudoattitude, unlike traditional attitude, provides a direct indication of the flight path. For coordinated flight, pseudoroll angle closely corresponds to traditional roll angle.[4] Figure 1a shows the velocity vector with respect to the ground $\boldsymbol{v}_g$, used for the definition of pseudoattitude, and the body axes (x_b, y_b, z_b) used for the definition of the traditional attitude.

Pseudoattitude is entirely observable from single-antenna GPS information. Pseudoattitude is synthesized from the velocity and acceleration vectors with respect to the ground, $\boldsymbol{v}_g$ and $\boldsymbol{a}_g$, respectively. These quantities can be computed from Doppler frequency shift measurements of the GPS carrier tracking loop in the navigation solution. In many commercially available GPS receivers, as with the receiver used for this research, acceleration states are not provided in the receiver navigation solution and have to be inferred externally. Because of the noise present in the receiver measurements, simple backdifferencing of the velocity measurements is not feasible. Instead, a Kalman filter can be used to estimate acceleration. For the research described in this paper, a Kalman filter with a triple integrator process model for estimating velocity, acceleration, and jerk states from velocity measurements was used. The latter state was included to model aircraft roll rate appropriately.[3]

Flight-path angle is defined as the angle between $\boldsymbol{v}_g$ and the local level ground plane and is given by

$$\gamma = \operatorname{atan}\left(-v_{gD} \middle/ \sqrt{v_{gN}^2 + v_{gE}^2}\right) \tag{1}$$

where the subscripts N, E, and D define north, east and down directions and a positive γ indicates a climb. The pseudoroll $\tilde{\phi}$ is determined from the known aircraft acceleration $\boldsymbol{a}_g$ and the gravitational acceleration $\boldsymbol{g}$ as shown in Fig. 1b. First, a pseudolift acceleration vector $\tilde{\boldsymbol{l}}$ is defined as the vector difference of $\tilde{\boldsymbol{a}}_g^n$ and $\tilde{\boldsymbol{g}}^n$, the components of $\boldsymbol{a}_g$ and $\boldsymbol{g}$ normal to the aircraft velocity vector $\boldsymbol{v}_g$, respectively. That is,

$$\tilde{\boldsymbol{l}} = \tilde{\boldsymbol{a}}_g^n - \tilde{\boldsymbol{g}}^n \tag{2}$$

where $\tilde{\boldsymbol{a}}_g^n$ and $\tilde{\boldsymbol{g}}^n$ are defined as

$$\tilde{\boldsymbol{a}}_g^n = \boldsymbol{a}_g - \left(\boldsymbol{a}_g \cdot \boldsymbol{v}_g \middle/ |\boldsymbol{v}_g|^2\right) \cdot \boldsymbol{v}_g \tag{3}$$

$$\tilde{\boldsymbol{g}}^n = \boldsymbol{g} - \left(\boldsymbol{g} \cdot \boldsymbol{v}_g \middle/ |\boldsymbol{v}_g|^2\right) \cdot \boldsymbol{v}_g \tag{4}$$

The pseudoroll angle $\tilde{\phi}$ is then determined as the complement of the angle between the pseudolift vector and a local horizontal reference $\tilde{\boldsymbol{p}}$:

$$\tilde{\phi} = \operatorname{asin}(\tilde{\boldsymbol{l}} \cdot \tilde{\boldsymbol{p}} / |\tilde{\boldsymbol{l}}| \cdot |\tilde{\boldsymbol{p}}|) \tag{5}$$

where the local horizontal reference is defined by

$$\tilde{\boldsymbol{p}} = \boldsymbol{g} \times \boldsymbol{v}_g = \tilde{\boldsymbol{g}}^n \times \boldsymbol{v}_g \tag{6}$$

The force diagram in Fig. 1b closely resembles the force diagram of an aircraft flying a coordinated turn. The only difference is that in the diagram of Fig. 1b the inertial velocity vector axis, that is, the axis aligned with $\boldsymbol{v}_g$, is used to resolve the forces instead of the axis aligned with the velocity vector relative to the air. However, for most flight conditions the two axes are closely aligned and pseudoroll angle corresponds closely to the traditional roll angle.[4]

There are flight conditions, such as during a severe slip, yaw maneuver, stall, or spin, where the assumption of coordinated flight does not hold true. In addition, during severe atmospheric nonuniformities, such as severe gusts, turbulence, and windshear, the inertial velocity vector axis and the velocity vector relative to the air may no longer be closely aligned. In these instances pseudoroll angle may differ considerably from the aircraft bank angle. The effects of uncoordinated flight conditions and severe atmospheric nonuniformities on pseudoroll are discussed in Ref. 4 in more detail.

III. Independent Backup Attitude Indicator

The traditional GA cockpit instrumentation is thought to provide insufficient attitude redundancy because, if the primary attitude system fails, the pilot is required to infer aircraft attitude from the remaining instrumentation. This approach is commonly referred to as flying with *needle, ball, and airspeed* and imposes a prohibitively large mental burden on the pilot. On the other hand, a pilot in a GA aircraft equipped with a GPS receiver may obtain GPS velocity-based pseudoattitude indication in addition to primary navigation information. This independent attitude source constitutes an additional level of redundancy that has the potential to greatly reduce the pilot's mental workload in case of a primary attitude system failure, and can thereby significantly increase aircraft safety.

This section discusses the experimental evaluation of the pseudoattitude system under several different flying conditions. The objective of the flight evaluation was to demonstrate the ability of a range of pilots to close the flight control loop around pseudoattitude and ultimately to show the ability of the pseudoattitude system to act as a backup aircraft attitude indicator.

A. Flight-Test Setup

The flight evaluation of the pseudoattitude system was conducted in an instrumented single-engine four-seat Piper Arrow aircraft. The instrumentation included a 12-channel coarse/acquisition (C/A) code GPS receiver as the primary GPS velocity source and a 5-channel C/A Code GPS/inertial navigation system (INS) unit as a reference for true aircraft attitude. The GPS receiver did not provide acceleration states in its single-point navigation solution. As mentioned in the preceding section, an external Kalman filter consisting of a triple integrator process model was used to estimate velocity, acceleration, and jerk states from velocity measurements.[3,4] The GPS receiver operated in a stand-alone nondifferential mode, and its output was, thus, affected by a number of errors including the effects of selective availability (SA). Both the GPS and the GPS/INS antenna were taped to the windshield inside the crew cabin close to the center of gravity. Satellite visibility during the flight tests typically fluctuated between five and nine satellites.

Both the GPS velocity data and the GPS/INS attitude data from the reference system were transmitted at an update rate of 10 Hz to a laptop computer over standard RS- 232 serial links. The laptop executed the attitude synthesizing algorithm and the acceleration estimating Kalman filter, and stored the acquired data for postflight analysis. Simultaneously, pseudoattitude was displayed in real time on the laptop computer screen at an update rate of 10 Hz. Figure 2a shows the simplified block diagram of the pseudoattitude system.

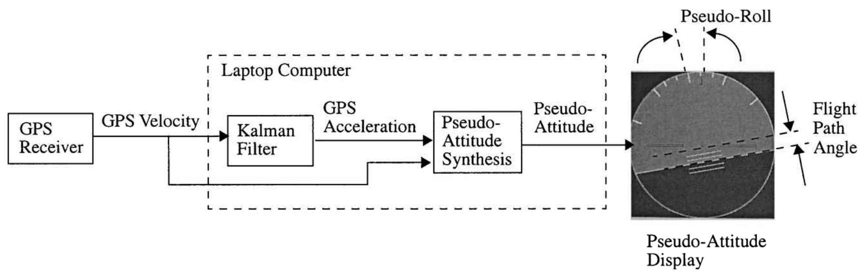


Fig. 2a Pseudoattitude system.

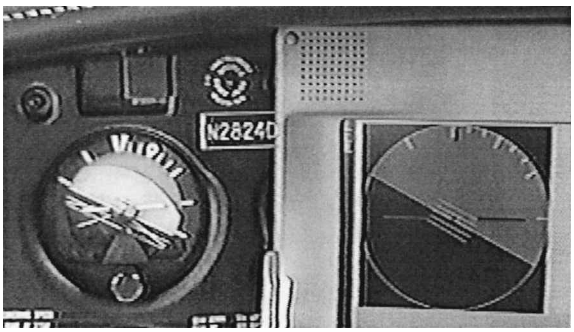


Fig. 2b Comparison of traditional attitude and pseudoattitude.

Table 1 Cooper–Harper subjective evaluation of pilot usability[a]

	Coordinated flight		Slip	
Pilot	Attitude indicator	Pseudoattitude display	Attitude indicator	Pseudoattitude display
A	2	2	——	——
B	3	3	5	3
C	3	roll 3, fpa 6	3	3
D	3	4	2	3
E	3	3	4	3
F	2	2	2	1

[a]The Cooper–Harper scale ranges from 1 to 10, where 1 is the highest rating.

Pseudoattitude was displayed in a manner similar to the way traditional attitude is displayed on an artificial horizon (Fig. 2b). The pseudoroll representation matched the conventional roll display, but the pitch information was replaced with the flight-path angle.

The flight evaluation consisted of several flight-test sessions:

1) In an initial flight test, the pseudoattitude system was evaluated by comparing it to the conventional pitch and roll attitude measured by the GPS/INS unit. In this, as well as in five subsequent flight tests, Instrument Flight Rules (IFR)-rated pilot subjects evaluated the usability of the pseudoattitude system by flying an number of coordinated and uncoordinated flight maneuvers. The sequence of coordinated flight-test maneuvers consisted of straight and level flight for 30 s, two shallow and two steep turns for a heading change of 90 deg, a 500-ft climb and a 500-ft descent during a 360-deg turn. For the purpose of this evaluation, shallow and steep turns were defined as bank angles of approximately 20 and 45 deg, respectively. The pilot subjects also performed an uncoordinated slip maneuver with full rudder deflection while maintaining a straight flight path.

2) In a separate flight test, a single pilot demonstrated the pseudoattitude system during an instrument landing system (ILS) approach. This served to illustrate the usability of pseudoattitude for approach tasks. The approach was flown to Runway 29 at Hanscom Airport located in Bedford, Massachusetts.

All of the flight tests were performed under simulated IFR conditions where the pilot had her/his view obscured with a hood. All flight-test maneuvers were additionally performed using the traditional attitude indicator to obtain baseline data. In addition to objective data acquired with the flight-test instrumentation, subjective pilot ratings of the display flown were obtained using the modified Cooper–Harper scale.[5]

B. Flight-Test Results and Discussion

Results from the flight tests are shown hereafter, including a comparison of single-antenna GPS-based pseudoattitude and traditional attitude measured by the GPS/INS unit. In addition, the pilot subjective evaluations of the pseudoattitude display are presented.

1. Comparison of Pseudoattitude and GPS/INS Reference Attitude

Comparisons of pseudoattitude and traditional roll and pitch angles measured by the GPS/INS unit for the sequence of coordinated maneuvers are shown in Fig. 3. The data for this particular test were taken in conditions of moderate turbulence with an average wind magnitude of 28 kn.

Figure 3a shows the comparison of pseudoroll and traditional roll for straight and level flight in moderate turbulence, where level flight was difficult to achieve. Figure 3b shows the comparison for steep turns. As can be seen, synthesized pseudoroll angle corresponds closely to traditional roll angle. A slight overshoot behavior in pseudoroll can be seen at instances where traditional roll changes abruptly. In addition, a lag of about 0.5 s is observable. Both the overshoot and the lag are closely tied to the Kalman filter characteristics.[4] A lower delay time and better overshoot behavior may be achievable with a different filter tuning at the expense of more noise in the estimate.

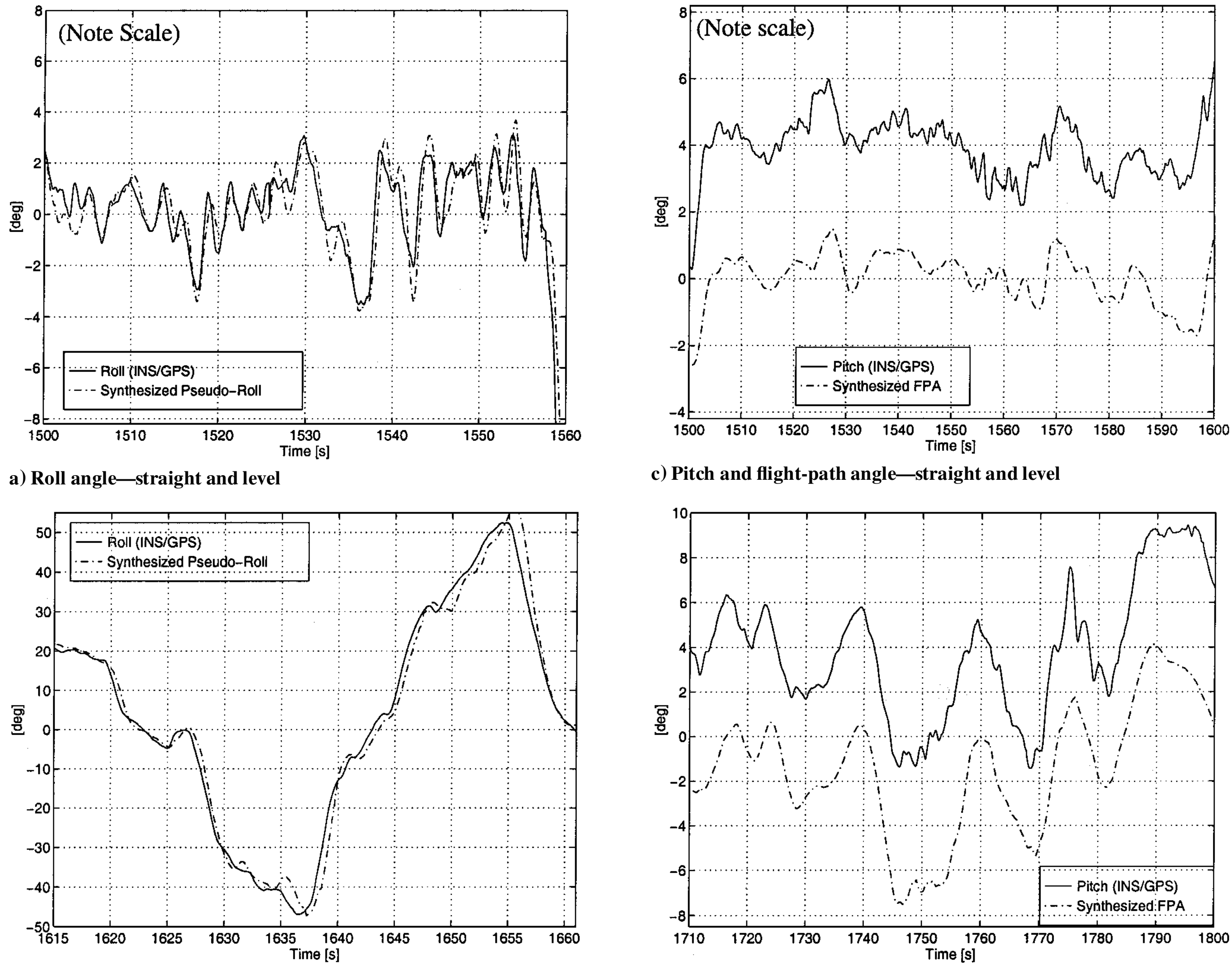
Figure 3c shows the comparison of synthesized flight-path angle and reference pitch angle during straight and level flight in the presence of moderate turbulence. Figure 3d shows the comparison for a 500-ft descent during a 360-deg turn. The plotted flight-path angle largely follows the pitch angle with an approximately constant offset. The difference between them is due to aircraft angle of attack. A high-frequency content is observable in the pitch angle that is not present in the flight-path angle. This is because pitch attitude is a control variable of higher bandwidth and is adjusted to achieve a desired flight-path angle.

Figure 2b shows a comparison of the traditional attitude and pseudoattitude displays during an approximately 30-deg level turn in one of the flight tests. As can be seen, the pseudoroll indication on the laptop computer screen (on the right) corresponds closely to the traditional roll indication on the panel mounted artificial horizon (on the left).

2. Subjective Evaluation of Pilot Usability of Pseudoattitude

The evaluation of pilot usability of the pseudoattitude system is based on flight tests performed by six IFR-rated pilots. The six flight tests were performed under wind conditions ranging from 28 up to 44 kn. Cooper–Harper subjective evaluations of the pseudoattitude system and the traditional attitude indicator for the different flight maneuvers are shown in Table 1. The Cooper–Harper scale ranges from 1 to 10, where 1 is the highest rating.[5]

Based on the six pilot evaluations, no significant difference is apparent between the two displays. The examination of the individual ratings reveals that in the case of coordinated flight, the pseudoattitude system performed equivalently to the traditional attitude indicator for the majority of pilots. Note that for the evaluation of pseudoattitude the pilot subjects had an unusual instrument scan pattern due to the position of the laptop computer screen held in



a) Roll angle—straight and level

c) Pitch and flight-path angle—straight and level

b) Roll angle—steep turn

d) Pitch and flight-path angle—500-ft descent in 360-turn

Fig. 3 Comparison of pseudoattitude and GPS/INS reference attitude.

front of them. One subject (pilot C) objected to some of the display features in the pitch ladder (insufficient space between bars on the pitch ladder) and, as a consequence, voluntarily separated the Cooper–Harper ratings for flight-path angle and pseudoroll.

For the slip maneuver, the pseudoattitude display shows a more consistent rating with four out of five pilots giving it an equal or better rating. This slightly better result for pseudoattitude may be attributable to the fact that to accomplish the maneuver, the pilot simply has to track zero pseudoroll angle in order to fly a straight flight track, whereas a constant roll angle must be held on the conventional artificial horizon.

3. *Results of Pseudoattitude-Based ILS Approach Flight Demonstration*

In a separate flight test, one pilot with low flight experience completed a pseudoattitude based ILS approach and a standard ILS approach using traditional attitude. Both approaches were successfully completed and control was never in question. At the time of testing gusts of 18 kn were present. Figure 4 shows the flight path of the two approaches to Runway 29. No substantial differences between them can be observed. Both flight paths feature slight oscillations in the lateral direction.

In the vertical direction, the conventional attitude-based approach path is offset from the reference path shown as a dotted line. This is primarily due to the slowly varying error induced by SA because the aircraft position data for all of the approaches were obtained from the same GPS receiver. Because of its correlation time of 2–5 min, the observed offsets may vary during the time two approaches are flown.

In addition, jumps in the vertical data of the pseudoattitude based ILS approach are observable. The jumps were due to changes in the satellite configuration tracked by the GPS receiver, which led to a new GPS position solution. The configuration changes were partly because of rising and setting satellites. Most of the time, however, they were caused by changes in aircraft attitude that brought satellites with low elevation angles into and out of the GPS antenna field of view. The availability of differential corrections, obtained for example from a differential GPS (DGPS) network, eliminates the effect of SA and reduces most of the impact of a changing satellite configuration on the position solution. Also, mounting the GPS antenna on top and bottom of the aircraft fuselage greatly increases the antenna field of view during turns and reduces the number of satellite configuration changes.

Figure 5 shows the lateral and vertical tracking errors in more detail. For comparison, a 100-ft lateral and 70-ft vertical tunnel window is shown. No substantial differences between the pilot tracking performance of the two ILS approaches are observable. Large lateral deviations that extend up to four times the tunnel width are apparent. In the vertical direction, the variation for both approaches are comparable to the tunnel height.

Table 2 indicates the standard deviation σ and peak-to-peak deviation Pp of the flight performance of the two approaches. For this evaluation, 50 s of data (512 samples) were selected from each approach in a common altitude range that extended from 800 to 1500 ft. The data were filtered using a fourth-order Butterworth filter with 0.4-Hz break frequency to mitigate the effects of the jumps that GPS satellite configuration changes introduced into the data. As expected, the values for the two approaches mostly indicate similar tracking performance.

For the statistical evaluation of the ILS data in this and subsequent sections it was assumed that the SA induced offset was constant and

Table 2 Deviations and Cooper–Harper ratings for ILS approaches

	Lateral deviation, ft		Vertical deviation, ft		
Approach	σ	*Pp*	σ	*Pp*	Cooper–Harper
Conventional attitude-based ILS (baseline)	201	569	39	136	4
Pseudoattitude-based ILS	129	390	40	180	5

that its influence was eliminated by considering the variations in the data. In reality, however, SA is slowly varying and may, therefore, appear as a flight technical error in the approaches flown using the ILS. Nonetheless, a typical SA-induced one-sigma error in velocity of 0.6 ft/s gives rise to a change of 30 ft during the 50-s time interval considered for the data evaluation. This error seems not to reduce the validity of the results, considering that the ILS approaches had deviations from the desired flight path of more than 300 ft.

Also given in Table 2 are the Cooper–Harper ratings for the traditional attitude and pseudoattitude displays under the experienced

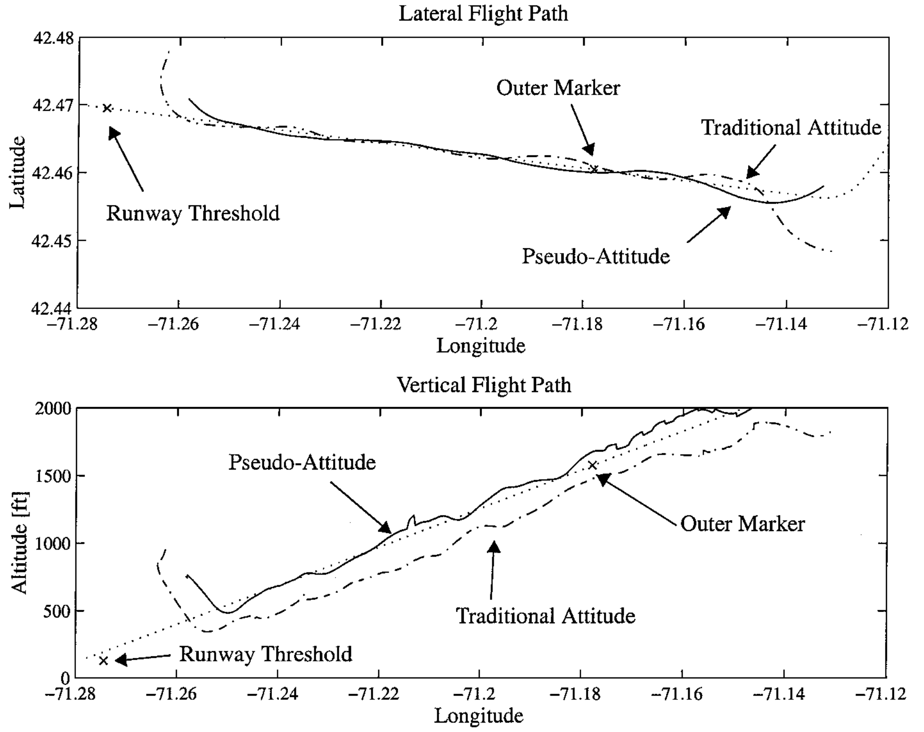


Fig. 4 Flight path of ILS approaches.

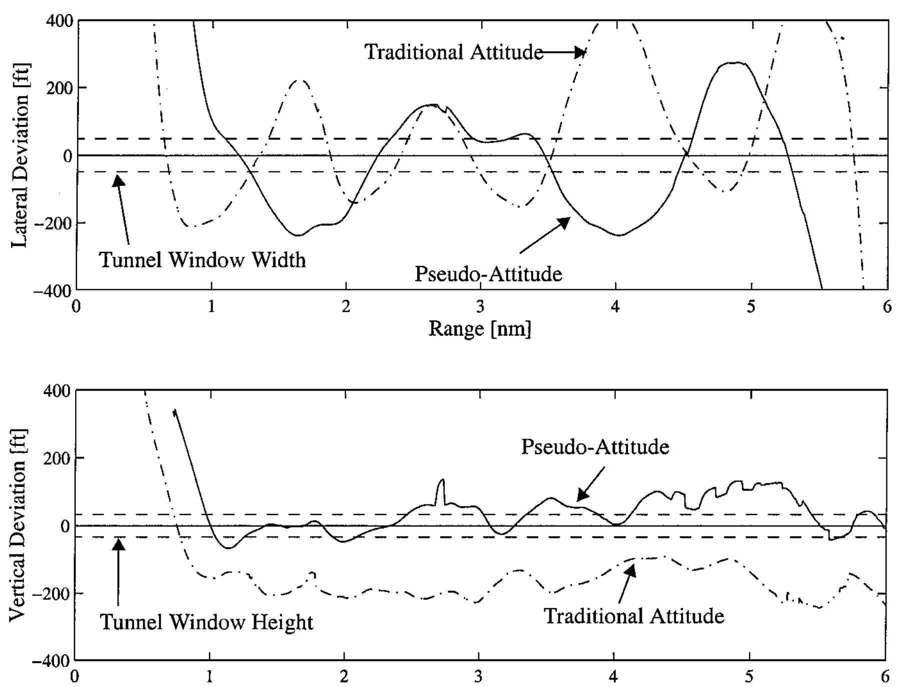


Fig. 5 Comparison of ILS approach flight-path deviations using pseudoattitude and traditional attitude control.

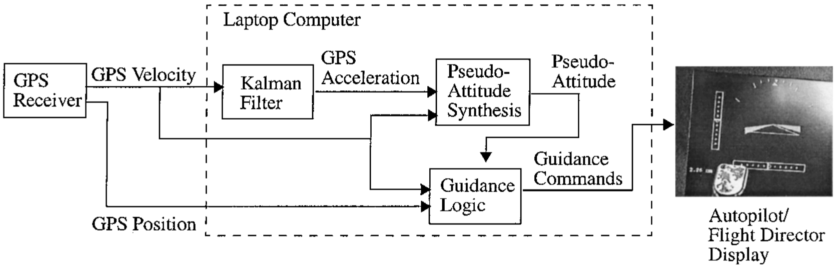


Fig. 6a GPS-based autopilot system.

approach conditions. The subject pilot gave the traditional attitude and the pseudoattitude-based ILS guidance systems a rating of 4 and 5, respectively. The rating of 4 indicated that the traditional attitude-based ILS guidance system had minor but annoying deficiencies, whereas the rating of 5 implied that the pseudoattitude-based system had moderately objectionable deficiencies. The pilot indicated that the higher Cooper–Harper rating for the pseudoattitude-based ILS guidance system was because of transient pseudoroll angle excursions that occurred in response to strong crosswind gusts.

4. Discussion

Several flight tests, consisting of coordinated and uncoordinated flight maneuvers as well as of an ILS approach, were successfully flown. These flight tests indicated that pseudoattitude is equivalent in performance to conventional attitude with no subjective or substantial objective differences between them. The results demonstrated the ability of the pilot to close the flight control loop around pseudoattitude and, hence, illustrated the ability of the pseudoattitude system to act as a backup attitude indicator.

IV. Single-Antenna GPS-Based Autopilot System

Recent developments of miniaturized UAV (micro UAV) call for a minimum of flight instrumentation in terms of mass, size, and power consumption. A single-antenna GPS receiver providing information for navigation, guidance, and flight control may, thus, be ideally suited to meet these goals. With this information, UAVs may be controlled using a single-antenna GPS-based autopilot system. Furthermore, this capability would provide the larger GA community with autopilot or flight director guidance because it is based solely on a readily available single-antenna GPS receiver.

In the preceding section, the ability of pilots to control the aircraft using pseudoattitude was successfully demonstrated under several different flight conditions. Both subjective and objective results indicated that pseudoattitude allows the pilot to achieve performance equivalent to what is achievable using traditional attitude. Although this indicated that a human pilot as a controller can close the flight control loop using pseudoattitude, it was not a priori evident that an autopilot or control law could do so as well. The question was thus raised as to whether GPS-based pseudoattitude could potentially be used to drive an aircraft autopilot system. To demonstrate the feasibility of an autopilot system that relied on pseudoattitude and other information obtained from a single-antenna GPS receiver, a pseudoattitude-based flight director/autopilot approach guidance logic was demonstrated in flight.

A. Flight-Test Setup

The flight tests were conducted in the Piper Arrow using mostly the same instrumentation as in the flight tests described earlier. A repeater display was additionally mounted in front of the pilot, repeating the information of the laptop computer screen, thereby greatly simplifying the pilot's scan pattern. The flight-test aircraft available was not equipped with a dual-axis autopilot, nor were actuators installed. Because the purchase and installment of the necessary equipment was not feasible under the scope of this flight demonstration, a different approach was pursued. This approach treated the pilot as an actuator promptly reacting to visual autopilot commands given on the display in front of the pilot in the form of standard flight director command bars. That is, a control law calculated the steering

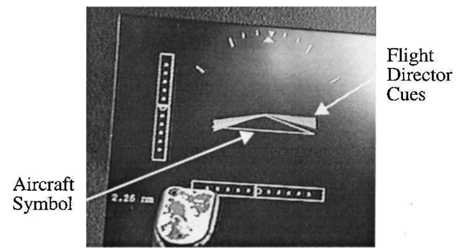


Fig. 6b Autopilot/flight director display.

commands. These were displayed to the pilot and the pilot implemented the commands by promptly actuating the steering wheel. Figure 6b shows the display on which the autopilot commands were conveyed to the pilot. The display depicted the aircraft symbol as a triangle fixed at the center of the display and flight director command bars in the shape of a shallow inverted V. The latter were a visual translation of the autopilot commands. Their vertical and rotational deviation from the aircraft symbol supplied to the pilot implicitly the flight path and pseudoroll angle necessary to establish the aircraft on the desired trajectory. The pilot was directed to capture and maintain the desired flight path by flying into the V symbol such that the command bars were aligned with the edges of the aircraft symbol. (Because of an error in the programming, the pseudoroll angle indicator and the localizer and glideslope indicators were not removed from the screen. These indicators were at the periphery of the screen, however, and the pilots indicated that they were able to ignore them and focus only on the flight director during the tests.) It was asserted that if a pilot, without obtaining any other visual or sensorial inputs, performed adequately in this pursuing task, then a pseudoattitude-based autopilot logic driving traditional actuators would be feasible.

Figure 6a shows the block diagram of the single-antenna GPS-based flight director/autopilot system. The autopilot guidance laws were designed to allow the capture and tracking of a desired trajectory. The longitudinal control law blended longitudinal tracking error and flight-path information to generate a longitudinal flight-path command. The lateral control law combined lateral tracking error and error rate as well as pseudoroll angle to yield a pseudoroll command. The actual control laws for longitudinal and lateral flight director (FD) commands were given by

$$\mathrm{FD}_{\mathrm{long}} = -K_\gamma \cdot (-K_h h - \gamma), \qquad \mathrm{FD}_{\mathrm{lat}} = (-K_d d - \dot{d}) \cdot K_{\dot{d}} - \tilde{\phi} \tag{7}$$

where h is the tracking error in longitudinal direction, γ is the flight-path angle, d and $\dot{d}$ are the tracking error and error rate in lateral direction, respectively, and $\tilde{\phi}$ is the pseudoroll angle. All quantities are angles and expressed in radians. K_h, K_γ, K_d, and $K_{\dot{d}}$ are the respective gains. The gains were set in initial simulator tests using a Cessna 182 simulator and further adjusted in preliminary flight tests. (The C182 aircraft model is publicly available and resembles in dimension and weight a Piper Arrow aircraft.) The gains were hereby iteratively adjusted to best satisfy pilot acceptance. The final values used were as follows: $K_h = 0.002$, $K_\gamma = -0.4422$, $K_d = 0.16\ \mathrm{s}^{-1}$, and $K_{\dot{d}} = 0.0162$ s. The flight director commands $\mathrm{FD}_{\mathrm{long}}$ and $\mathrm{FD}_{\mathrm{lat}}$ were translated into vertical and rotational deviation angles of the inverted V symbol with respect to the aircraft symbol. For instance, a rotation to the right of the V symbol with respect to the aircraft symbol indicated to the pilot that additional right bank was required to maintain the proper trajectory. Similarly, an upward translation of the V symbol with respect to the aircraft triangle indicated the need for increased flight-path angle.

Note that, for the purpose of this flight demonstrations, the lack of differential corrections to the GPS data was not considered fundamental. The flight tests were intended to demonstrated the flyability of a single-antenna GPS-based autopilot system, not to characterize well-understood and correctable errors in the GPS data. It was assumed that future implementations of single-antenna GPS-based autopilot systems would include some means of acquiring and incorporating the differential correction signal.

The flight test consisted of approaches flown to Runway 29 at Hanscom Airport located in Bedford, Massachusetts. For each approach, clearance from air traffic control (ATC) had to be obtained. All of the flight tests were performed under simulated IFR conditions where the pilot had her/his view obscured with a hood.

B. Flight-Test Results and Discussion

Two pilots successfully flew approaches to the missed approach point using the attitude command display. One pilot had low and the other had extensive flight experience. The wind conditions during the tests were 12 kn with gusts up to 18 kn. Aircraft control was never in question. The lateral and vertical tracking performance is plotted in Fig. 7. For comparison, a 100-ft lateral and 70-ft vertical tunnel window is shown. It is apparent that both subject pilots (subjects A and B) closely followed the desired flight path once passing the outer marker and stayed well within this imaginary tunnel for the most part of the approaches.

In addition, the deviations of the ILS approach flown with traditional attitude, discussed in the preceding section, are shown in Fig. 7. The comparison reveals two interesting differences. First, the oscillation amplitude of the ILS-based approach flight-path deviations in the lateral direction were in some instances more than four times larger than the corresponding tracking error obtained using the human-actuator autopilot. The variations in vertical direction seem comparable, however. Second, it is apparent that the oscillation frequency of the tracking errors obtained with human-actuator autopilot are higher than the oscillation frequency of deviations of the traditional attitude-based ILS approach. This suggests that the human-actuator-based autopilot system results in higher bandwidth control system.

In the vertical direction, the conventional attitude-based ILS approach path is offset from the reference path shown as a dotted line. As discussed in the preceding section, the offset is primarily due to the slowly varying error induced by SA. This problem did not exist for the GPS-based approaches because SA-induced errors would immediately be reflected as changes in the location of the assumed reference flight path used in the autopilot logic. In addition, small jumps in the GPS data are observable in the altitude data and are the result of configuration changes in the satellites tracked by the GPS receiver.

Table 3 gives a summary of the standard deviations σ and peak-to-peak values Pp of the tracking error for the two human-actuator autopilot approaches and the ILS approach. It is based on the evaluation of 50 s of data (512 samples) from each approach in a common altitude range from 800 to 1500 ft. To mitigate the effects of the jumps that GPS satellite configuration changes introduced into the data, the data were filtered using a fourth-order Butterworth filter with 0.4-Hz break frequency. As can be seen, better lateral tracking was achieved using the GPS-based autopilot system compared to the traditional ILS guidance.

C. Discussion

These results, as well as observations made during the flight tests, indicated the feasibility of a pseudoattitude-based autopilot system that relied on pseudoattitude and, consequently, on information entirely obtained from a single-antenna GPS receiver. Using the pseudoattitude-based autopilot system, the subject pilots achieved

Table 3 Standard deviation and peak-to-peak value of tracking error

	Lateral deviation, ft		Vertical deviation, ft	
Approach	σ	Pp	σ	Pp
Autopilot: subject A	20	83	25	108
Autopilot: subject B	14	52	8	40
Conventional attitude-based ILS	201	569	39	136

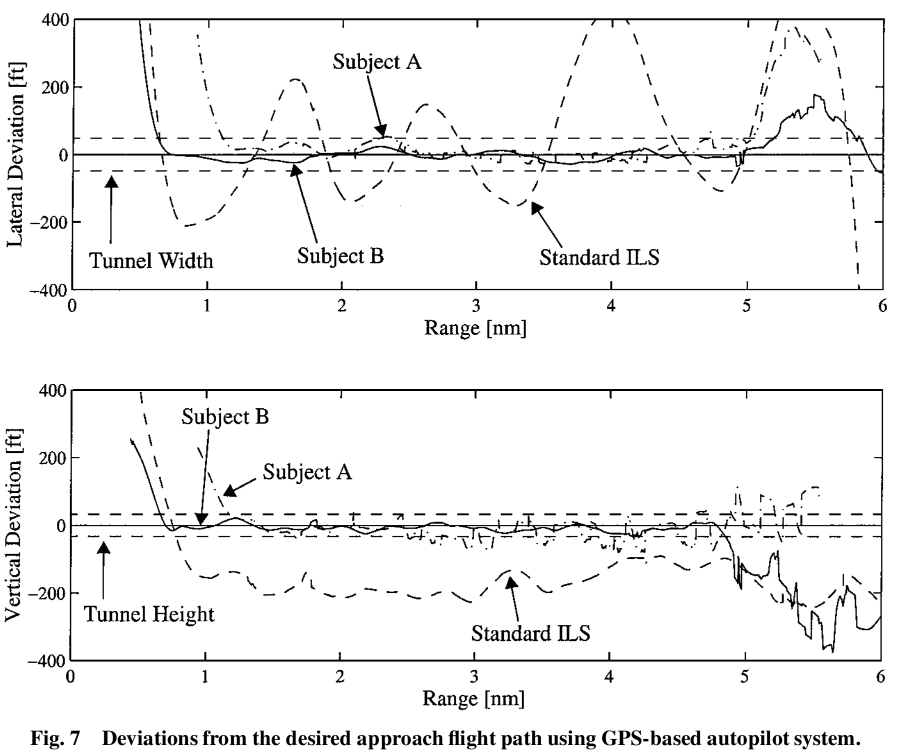


Fig. 7 Deviations from the desired approach flight path using GPS-based autopilot system.

better lateral tracking performance and higher control bandwidth than with traditional ILS approach guidance.

V. Pseudoattitude-Based Tunnel-in-the-Sky Trajectory Guidance System

A number of recent studies proposed tunnel-in-the-sky displays as alternatives to conventional guidance displays.[6,7] Tunnel-in-the-sky trajectory guidance systems provide the pilot with a perspective flight-path display that depicts the outside world in the form of a horizon and the desired flight path in the form of tunnel gates. The horizon information is typically obtained from an attitude sensing instrument. Additional guidance cues, such as deviation indicators, flight director cues, or trajectory predictors, may be included in these displays.

Tunnel-in-the-sky trajectory guidance systems rely on instantaneous aircraft attitude, velocity, and position information to provide trajectory guidance to the pilot. Thus far, only sensors such as INS and attitude and heading reference systems (AHRS), in conjunction with additional navigation sensors, or, more recently multiantenna GPS receivers had the capability to provide this information. However, these sensors and, in some cases, the need to fuse the information from different sensors, render these systems costly and often prevent their use in GA aircraft.

What fundamentally distinguishes the approach presented in this paper from the previous implementations is the use of single-antenna GPS-based pseudoattitude to drive the horizon on the perspective flight-path display. The use of position, velocity, and now pseudoattitude information, obtained from a single-antenna GPS receiver, eliminates the aforementioned shortcomings and reduces the cost of these systems sufficiently to make them available to the larger GA community. With the emergence of various differential GPS networks, an inexpensive GPS-based trajectory guidance system could provide guidance for complicated flight paths and allow precision approaches to be flown at airports that do not provide ILS capability.

To demonstrate the feasibility of a trajectory guidance system that relied entirely on information provided by a single-antenna GPS receiver, a pseudoattitude-based tunnel-in-the-sky trajectory guidance system using single-antenna GPS was demonstrated in flight.

A. Flight-Test Setup

The flight tests were conducted in a Piper Arrow using the same instrumentation as in earlier tests. Three systems for providing approach guidance were evaluated and compared in this flight-test demonstration: the standard ILS as a baseline, a single-antenna GPS-based system with a tunnel-in-the-sky display, and a single-antenna GPS-based system with a combined tunnel-in-the-sky and flight director display.

1. Standard ILS

The standard aircraft instrument panel with an ILS instrument served as the baseline for the comparison with the single-antenna GPS guidance systems. The standard aircraft instrument panel provided conventional attitude, heading, altitude, vertical speed, and airspeed indications, as well as other information. The standard ILS display indicated the position of the aircraft with respect to a vertical beam (glideslope) and a horizontal beam (localizer) transmitted from the runway. The ILS measurements consisted of angle information and the position accuracy increased with decreasing range to the runway.

2. Single-Antenna GPS System with Tunnel-in-the-Sky Display

The tunnel-in-the-sky display gave the pilot a perspective view of the outside world in the form of a horizon and showed the desired flight trajectory in the form of a tunnel. It took advantage of the three-dimensional positioning capabilities of GPS to locate the aircraft with respect to the desired flight path where, unlike the ILS, the position accuracy was independent of the range to the runway. In the implementation used in this flight demonstration, the horizon was driven by pseudoattitude synthesized from GPS velocity measurements. The trajectory guidance system generated a set of tunnel gates that were displayed to the pilot and represented the desired approach trajectory. To stay on course, the pilot had to fly through the gates.

Figure 8b shows the tunnel-in-the-sky display. The display partially adopted the symbology used by Refs. 6 and 7. The tunnel was superimposed on the horizon, which also featured a pseudoroll marker, a flight-path angle ladder, and a ground track heading indication. The aircraft symbol was shaped like a triangle and fixed at the center of the horizon display. It indicated the pseudoattitude of the aircraft with respect to the horizon. The tunnel size corresponded to an area of 100 ft horizontally and 70 ft vertically. The tunnel featured a specially colored gate (orange) indicating the middle marker. Glide slope and localizer deviation indicators were shown to the left and at the bottom of the horizon, respectively. Additional display information included an altimeter tape and vertical speed indicator at the right side and a ground speed tape at the left side of the display. A separate ground track heading compass indicator and the distance to runway were provided at the bottom of the display. As stated earlier, the entire display was driven by information obtained from a single-antenna GPS receiver. The flight director command bars shown in the center of Fig. 8b were not included in the tunnel-in-the-sky display.

3. Single-Antenna GPS System with Combined Tunnel-in-the-Sky and Flight Director Display

This system augmented the tunnel-in-the-sky display with an additional flight director. The flight director command bars had the shape of a shallow inverted V, as shown in the center of Fig. 8b. The flight director command bars were driven by the same guidance logic that was used for the demonstration of the pseudoattitude-based autopilot system, described in the preceding section. A block diagram of the GPS-based tunnel-in-the-sky trajectory guidance system is shown in Fig. 8a.

4. Flight-Test Protocol

The entire flight test was flown under simulated instrument conditions to limit the factors influencing the pilot's flight performance to the guidance system provided during the experiment. To accomplish this, the pilot wore a hood and the pilot's field of view was, therefore, restricted to the instrument panel.

After training and familiarization was completed, the pilot flew the three guidance systems according to a partially counterbalanced test matrix. Typically, a missed approach was flown once the aircraft reached an altitude of approximately 500 ft. In addition to objective data acquired using the flight test instrumentation, subjective pilot ratings for the particular guidance system flown were obtained after each approach using the modified Cooper–Harper scale. After the aircraft had landed, the pilot subject performed an analytic hierarchy process (AHP) to assess the overall subjective preference of the displays.[8]

B. Flight-Test Results and Discussion

Three pilots served as experimental subjects to evaluate the GPS-based trajectory guidance system. Results from the flight tests are shown below. They include qualitative observations and statistical analysis of the flight performance as well as subjective evaluations of the different trajectory guidance systems.

1. Qualitative Observations of Flight Performance

All of the approaches were successfully flown to the missed approach point or the point where ATC requested a missed approach because of traffic. Aircraft control was never in question. A representative example of the flight performance observed is shown in Fig. 9. It depicts the lateral and vertical deviations from the desired flight paths of the approaches flown by subject pilot 3 to Runway 29, with the tunnel dimensions indicated by dashed lines. Figure 9 offers a qualitative look at the flight performance during the approaches. The data, as well as observations made during all of the flight tests, suggest that the flight performance of approaches flown using both GPS guidance systems was at least comparable to, and most of the time better than, that the flight performance of approaches flown using the standard ILS. For the approaches flown using both GPS guidance displays, the aircraft for the most part stayed within the tunnel. The approach flown using the standard ILS, however, shows

Table 4 Flight performance summary of different trajectory guidance systems

		Lateral deviation, ft						Vertical deviation, ft					
		ILS (baseline)		Tunnel (GPS)		Combined (GPS)		ILS (baseline)		Tunnel (GPS)		Combined (GPS)	
Pilots	Altitude range, ft	σ	Pp	σ	Pp	σ	Pp	σ	Pp	σ	Pp	σ	Pp
1	800–1300[a]	132	381	30	97	8	33	16	72	21	103	13	80
2	800–1500	58	196	9	32	6	25	26	245	8	38	15	56
3	800–1500	201	569	30	119	26	103	39	136	12	46	47	211

[a]Because of incomplete data acquisition, the data analyzed for the ILS approach was taken from 300–700 ft.

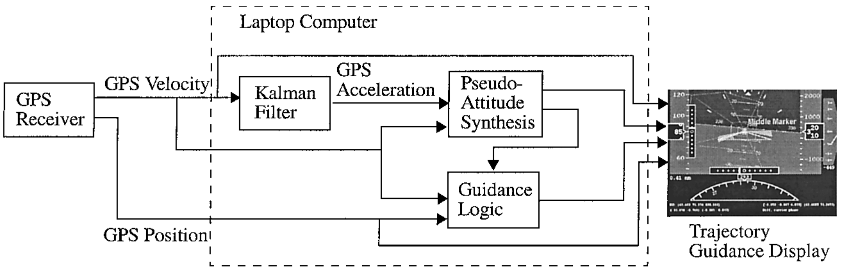


Fig. 8a GPS-based trajectory guidance system.

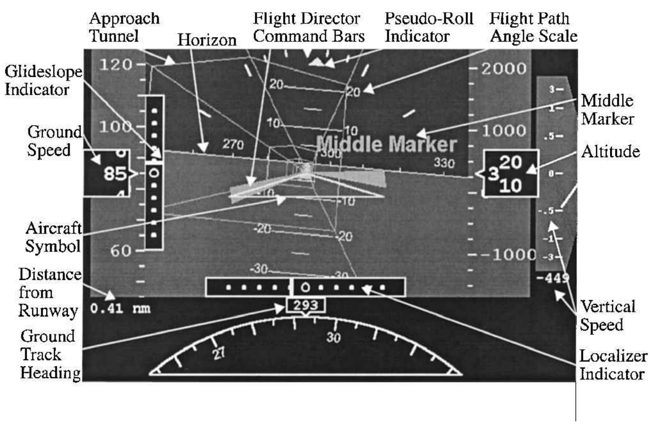


Fig. 8b Combined tunnel-in-the-sky and flight director display.

oscillations in lateral tracking performance with much larger amplitude, which in certain cases extend to four times the tunnel dimensions. The variations in vertical deviation appear comparable to the ones experienced with both GPS guidance displays.

It can be further observed that the approach paths based on the GPS guidance system contain oscillations at higher frequency, compared to the oscillations of the ILS-based approaches. This suggests that the tunnel-in-the-sky display (with or without the flight director) provided feedback, that allowed higher control bandwidth and, at the same time, resulted in increased physical workload for the pilot because more frequent adjustments to the flight path were made.

Two effects, caused by the lack of differential GPS corrections, are observable in Fig. 9. Large jumps in the GPS data, particularly apparent in the altitude data, led to an instantaneous change of the tunnel position on the display. This caused the aircraft to suddenly fly outside the tunnel and prompted the pilot to reacquire the tunnel. These jumps were the result of a configuration change of the satellites tracked by the GPS receiver, which led to a new GPS position solution. The second effect was the nearly constant offset between the ILS and the GPS trajectories, particularly apparent in the vertical data. This was assumed to be mainly due to the presence of SA.

2. Analysis of Flight Performance

The flight performance is evaluated quantitatively using approximately 50 s of data (512 samples) in a common altitude range for all of the approaches. The data were filtered using a fourth-order Butterworth filter with 0.4-Hz break frequency to mitigate the effects of the jumps that GPS satellite configuration changes introduced into the data. In addition, nonphysical jumps in the data recorded during the ILS approach were removed. This was not possible for the data recorded during the approaches using the GPS trajectory guidance systems because the jumps were apparent to the pilot and the pilot compensated for them. Table 4 shows the standard deviations σ and peak-to-peak values Pp of the lateral and vertical tracking errors for the three guidance systems. Also shown are the altitude ranges chosen for the data analysis. All of the values are expressed in feet.

One way to compare the performance of approaches flown with two trajectory guidance systems is to consider the difference of their respective performance metrics, that is,

$$\text{Difference}_{\sigma} = \sigma_{\text{Guidance System } A} - \sigma_{\text{Guidance System } B}$$

$$\text{Difference}_{Pp} = Pp_{\text{Guidance System } A} - Pp_{\text{Guidance System } B} \qquad (8)$$

This assumes that the difference in performance is only due to the different guidance systems with the error induced by the pilot's flying skills remaining constant. Alternatively, the ratio of a performance metric may be used as a comparison for the approaches flown with two of the guidance systems, that is,

$$\text{Ratio}_{\sigma} = \frac{\sigma_{\text{Guidance System } A}}{\sigma_{\text{Guidance System } B}}, \qquad \text{Ratio}_{Pp} = \frac{Pp_{\text{Guidance System } A}}{Pp_{\text{Guidance System } B}} \qquad (9)$$

This approach models the effects of the pilot skill level as a constant gain (that is, a more skilled pilot will always perform better than a less skilled pilot regardless of the guidance system used) and gives an indication of the percentage performance improvement obtained when using one system over the other.

Table 5 shows the results of a pairwise comparison among the three guidance systems. The entries are the difference and the ratio of the performance metrics for two systems, averaged over all three pilot subjects. For instance, the peak-to-peak lateral deviations for the ILS approaches were on average more than eight times larger than the corresponding values for the combined tunnel-in-the-sky and flight director guidance system.

To examine the statistical significance of these comparisons, a 5% one-tailed t test was performed. The comparisons for which the differences in flight performance were significant are noted in Table 5. The approaches flown using both GPS-based guidance systems show significantly better lateral tracking performance compared to the ILS-based approaches. On the other hand, no significant difference in lateral tracking performance can be observed between the two GPS-based systems. Also, no significant difference in vertical tracking performance for any of the guidance systems is apparent. These results are in good correspondence with the qualitative observations made earlier.

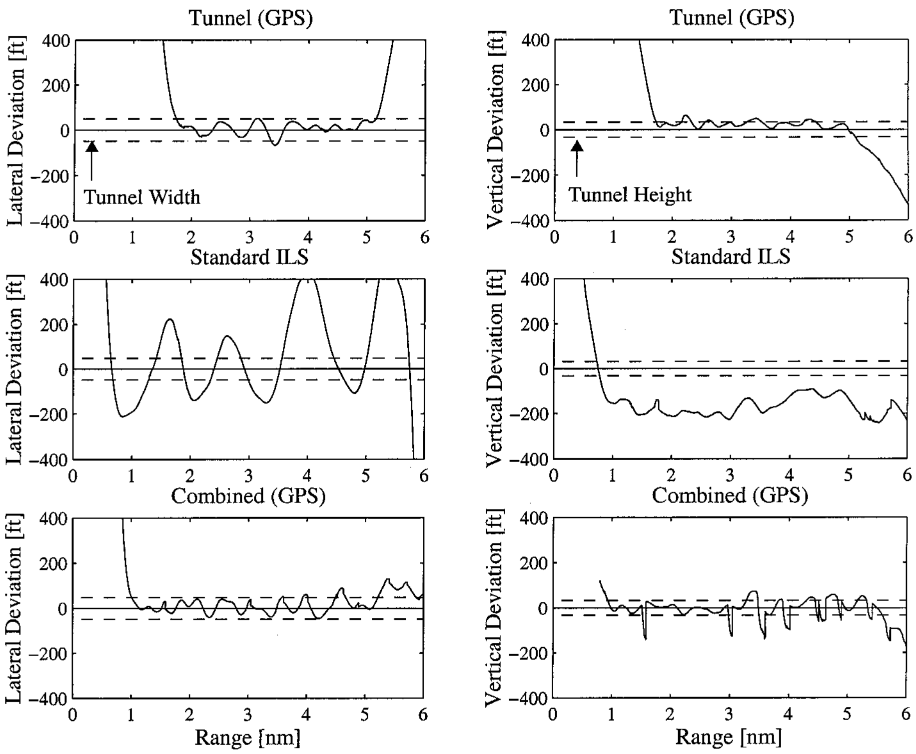


Fig. 9 Representative deviations from the desired approach flight path using different approach guidance systems.

Table 5 Pairwise comparison of flight performance

	ILS vs tunnel		ILS vs combined		Tunnel vs combined	
Parameter	σ	*Pp*	σ	*Pp*	σ	*Pp*
			Lateral deviation			
Difference, ft	107[a]	299.7[a]	117[a]	329[a]	9	29
Ratio	5.9[a]	5.0[a]	11.2[a]	8.3[a]	2.1	1.8
			Vertical deviation			
Difference, ft	13	89	2	35	−11	−53
Ratio	2.4	3.3	1.3	2.0	0.8	0.7

[a]Significant difference in flight performance is shown.

An important point has to be considered before drawing conclusions from these results, namely the lack of an independent measurement of the aircraft position. The aircraft position data for all of the approaches was obtained from the same GPS receiver that provided the information for the GPS-based trajectory guidance systems. Because the GPS measurements were obtained in a stand-alone nondifferential mode, they were affected primarily by SA. This had two immediate consequences. Changing satellite configurations gave raise to jumps in the recorded GPS data. For the approaches flown using the ILS, these jumps could be removed during postprocessing. This was not possible for the approaches flown with the GPS guidance systems because the pilots could observe the jumps and compensate for them. These jumps, therefore, appear to degrade the flight performance for the GPS-based guidance systems more than for the ILS approaches.

3. Subjective Evaluation of Trajectory Guidance Systems

The subjective ratings were given by the pilots for each of the guidance systems using the modified Cooper–Harper scale. Based on the three pilot evaluations, no significant difference between any of the guidance systems could be observed. With the exception of two instances, a rating of 4 was given in all cases, indicating that the display characteristics had minor but annoying deficiencies that required moderate pilot compensation. Two subjects gave the tunnel-in-the-sky guidance option a rating of 5 because they objected to the GPS-induced jumps of the tunnel that they experienced while flying this approach. This rating corresponds to moderate objectionable display deficiencies requiring the pilot to apply considerable compensation to achieve adequate performance.

The AHP for the three guidance options was performed.[8] The AHP allows for the ranking of multiple systems under evaluation in the order of preference. It thereby considers the relative size of the intervals between the ranking. The AHP is performed through a series of paired comparisons that are recombined to produce an overall weighted ranking. The results indicated a weak pilot preference for the combined tunnel-in-the-sky and flight director display compared to the standard ILS guidance option. No clear preference between the GPS-based tunnel in the sky and the ILS was apparent.

4. Discussion

These flight-test results demonstrated the feasibility of a tunnel-in-the-sky trajectory guidance system that was based on pseudoattitude for inner-loop control and, consequently, relied on information entirely provided by a single-antenna GPS receiver. Qualitative observations as well as the quantitative assessment of the data collected during the approaches suggested that the GPS-based trajectory guidance systems (with or without flight director) allowed for a significant reduction in the lateral tracking errors when compared to the ILS system. No significant differences were found between the two GPS-based guidance systems, nor among all of the three guidance systems for vertical flight performance. Although Cooper–Harper ratings from all of the pilots indicated a similar level of deficiency among the three trajectory guidance systems, there existed a preference by the pilots for the combined tunnel-in-the-sky and flight director display.

VI. Conclusions

Three applications of GPS velocity-based attitude information were successfully demonstrated in flight. A pseudoattitude-based backup attitude indicator was demonstrated in flight and was shown to act in a functionally equivalent manner as traditional attitude with no subjective or substantial objective differences to traditional attitude. Next, a pseudoattitude-based autopilot/flight director system was demonstrated in flight. Using the pseudoattitude-based flight director system, the pilots achieved better tracking performance and higher control bandwidth than with traditional ILS approach guidance. Last, a GPS-based tunnel-in-the-sky trajectory guidance system was successfully demonstrated.

Unlike traditional attitude indicators and autopilot and trajectory guidance systems, these applications rely solely on the information obtained from a single-antenna GPS receiver. Moreover, GPS velocity-based pseudoattitude information has a number of beneficial attributes. Because no alignment or specific aircraft information is required, the implementation of these applications in a stand-alone, hand-held configuration is particularly appealing. In fact, the instrumentation used throughout a large part of the flight tests documented in this paper was portable. Furthermore, GPS-based pseudoattitude relies entirely on solid-state integrated circuit technology and, thus, allows implementations with lower weight, size, and power consumption and at typically lower cost than traditional attitude-sensing instrumentation. Pseudoattitude based applications have, thus, significant system integration and cost advantages that make these glass-cockpit capabilities affordable to the GA aircraft community.

To successfully apply pseudoattitude-based applications, however, their limitations have to be taken into account. Based on the projected GPS integrity and availability levels, the use of GPS as a sole means attitude and flight control sensor for piloted aircraft is likely premature. In addition, the assumption of coordinated flight, inherent in the generation of pseudoattitude information, sets some limitations on the allowable aircraft flight envelope. Consequently, to accommodate these limitations, pseudoattitude-based systems are currently best used as supplemental systems in piloted aircraft and, depending on the required level of integrity, may be used as supplemental or sole means systems in unpiloted vehicles such as small, expendable UAVs.

Acknowledgments

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