Attitude Adjustment

Devising and Flying a Low-Cost GPS-Based Backup

RICHARD KORNFELD

General aviation pilots often find themselves caught between a desire to keep equipment costs low and yet ensure redundancy in case of failure of a critical flight instrument. This article describes the implementation and test of a low-cost, GPS-based backup attitude indicator that relies on a $150 GPS receiver board, a popular PDA and an algorithm originally developed at MIT. The resulting system computes "pseudo-attitude" information, consisting of roll and flight path angle, from GPS velocity updates, and displays it on the PDA by emulating a typical artificial horizon.

How many times, while flying in the thick of things, did we wish aviators had something better than "needle, ball and airspeed" at our disposal in case the attitude indicators fails?

Granted, needle, ball and airspeed — that is, turn coordinator and airspeed indicator — get the job done and have saved many lives along the way. Still, the mental workload required when flying this set of instruments is considerable, and this skill needs to be carefully honed.

Unfortunately, many cockpits of general aviation (GA) aircraft are still equipped with only a single attitude indicator, and pilots have to rely on needle, ball, and airspeed as their backup option in case their primary instrument fails. Although an increasing number of glass cockpit–equipped GA aircraft are emerging in today's market that do provide redundancy, the majority of the GA fleet does not benefit from this leap in technology because of the high cost of these systems.

On the upshot, technology advances have enabled some aircraft operators to get an affordable back-up option over the years, such as handheld radios or GPS moving maps. The latter typically indicate ground track as well, which may serve as a substitute for heading, if need be. But wouldn't it be nice to have a handheld backup attitude indicator as well?

The following article describes a low-cost, handheld, single-antenna, GPS-based aircraft attitude indicator that we recently flight-tested. While a number of companies have commercial products on the market that emulate cockpit instrumentation displays, these devices typically cost several hundreds (or thousands) of dollars, display merely turn rate (not attitude), are limited by a low update rate, and thus are not suitable to provide meaningful aircraft attitude information. The attitude indicator described in this article, on the other hand, displays attitude information at a high update rate and relies on a $150 GPS receiver and a portable digital assistant (PDA).

Single-Antenna GPS-Based Attitude

Research performed a few years ago by the author, John Hansman, and John Deyst at the Massachusetts Institute of Technology (MIT) addressed this question and resulted in an approach to obtain attitude information from a single-antenna GPS receiver. Some of the original publications are listed in “Additional Resources” at the end of this article.

We derived this approach from a basic notion taught in every ground school: When the aircraft is flown in a coordinated turn (“ball in the middle”), then the turn rate and the roll angle are closely related to each other. The turn rate itself can be derived from the velocity information that the GPS receiver provides. That is, by using the measured lateral rate of change of the velocity vector, a roll substitute can be computed.

We demonstrated that under coordinated flight conditions, the computed roll angle corresponded very closely to the roll angle shown on traditional attitude indicators. 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. We can show that the synthesized attitude information is also useful in the presence of moderate sideslip conditions.

The second attitude component used in this approach is flight path angle. This can also be derived from velocity information measured by the GPS receiver and used in place of the traditional pitch indication. In fact, flight path angle is offset from the latter by the angle of attack and is a direct indication of the aircraft flight path.

We generally refer to the set of computed roll angle and flight path angle as *pseudo-attitude* to distinguish it from the traditional attitude as provided by a vacuum pump–driven attitude indicator in a GA aircraft. Figure 1(a) shows the velocity vector with respect to the ground, $\mathbf{v}_g$, used for the definition of pseudo-attitude, and the body axes, (x_b, y_b, z_b), used for the definition of the traditional attitude.

Specifically, flight path angle is defined as the angle between $\mathbf{v}_g$ and the local level ground plane and is given by

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

where the subscripts *N*, *E*, and *D* define *north*, *east*, and *down* directions, and a positive γ indicates a climb. The pseudo-roll $\tilde{\phi}$ is determined from the known aircraft acceleration $\mathbf{a}_g$ (a quantity derived from velocity information to be discussed) and the gravitational acceleration $\mathbf{g}$ as shown in Figure 1(b). First, a pseudo-lift acceleration vector $\tilde{\mathbf{l}}$ is defined as the vector difference of $\tilde{\mathbf{a}}_g^n$ and $\tilde{\mathbf{g}}^n$, the components of $\mathbf{a}_g$ and $\mathbf{g}$ normal to the aircraft velocity vector $\mathbf{v}_g$, respectively. That is,

$$\tilde{\mathbf{l}} = \tilde{\mathbf{a}}_g^n - \tilde{\mathbf{g}}^n \qquad (2)$$

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

$$\tilde{\mathbf{a}}_g^n = \mathbf{a}_g - \left(\mathbf{a}_g \bullet \mathbf{v}_g \Big/ \left|\mathbf{v}_g\right|^2\right) \cdot \mathbf{v}_g \qquad (3)$$

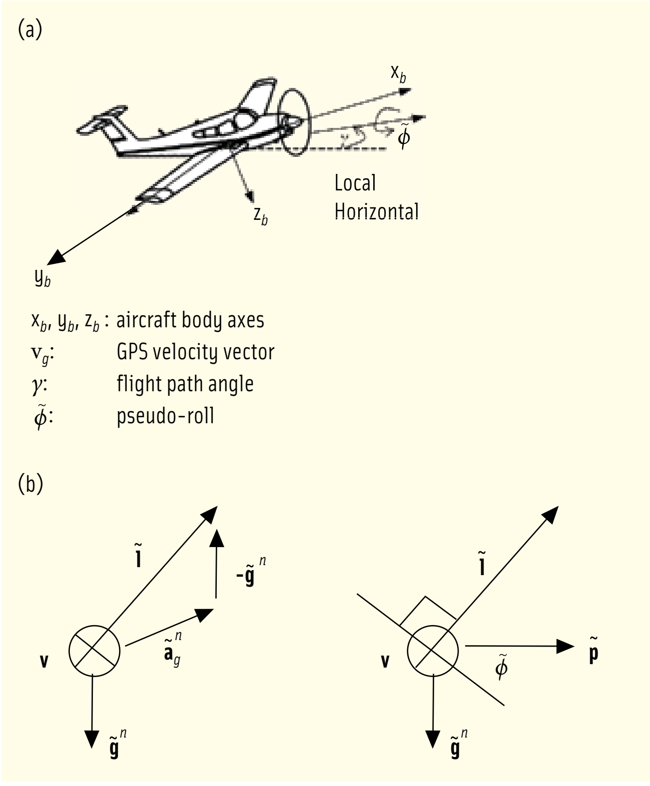


FIGURE 1 (a) Illustration of pseudo-attitude, (b) Determination of pseudo-roll

$$\tilde{\mathbf{g}}^n = \mathbf{g} - \left(\mathbf{g} \bullet \mathbf{v}_g \Big/ \left|\mathbf{v}_g\right|^2\right) \cdot \mathbf{v}_g \qquad (4)$$

The pseudo-roll angle $\tilde{\phi}$ is then determined as the complement of the angle between the pseudo-lift vector and a local horizontal reference $\tilde{\mathbf{p}}$

$$\tilde{\phi} = \operatorname{asin}\left(\tilde{\mathbf{l}} \bullet \tilde{\mathbf{p}} \Big/ \left|\tilde{\mathbf{l}}\right| \bullet \left|\tilde{\mathbf{p}}\right|\right) \qquad (5)$$

where the local horizontal reference is defined by

$$\tilde{\mathbf{p}} = \mathbf{g} \times \mathbf{v}_g = \tilde{\mathbf{g}}^n \times \mathbf{v}_g \qquad (6)$$

The force diagram in Figure 1(b) closely resembles the force diagram of an aircraft flying a coordinated turn. The only difference is that in the diagram of Figure 1(b) the inertial velocity vector axis, that is, the axis aligned with $\mathbf{v}_g$, is used to resolve the forces instead of the axis aligned with the velocity vector relative to the air.

This approach has a number of advantages. First, because pseudo-attitude is entirely observable from GPS velocity measurements, a GPS receiver is the only sensor needed. Next, none of the hardware needs to be permanently mounted to the aircraft; so, a pilot can implement the system as a handheld device.

To get a good pseudo-attitude indication, however, the velocity information $\mathbf{v}_g$ needs to be derived from Doppler measurements of the GPS carrier tracking loop, a standard feature in high-end GPS receivers. This results in better veloc-

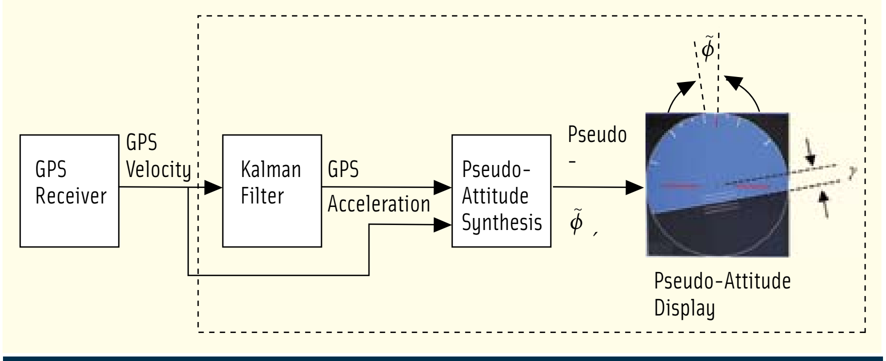


FIGURE 2 Block diagram of pseudo-attitude system

ity measurements than by simply differentiating GPS positions. The acceleration vector a_g has to be derived externally because in many commercially available GPS receivers, as with the receiver used for this demonstration, acceleration states are not provided in the receiver navigation solution.

For the demonstration described in this article, we used a Kalman filter with a triple integrator process model to estimate velocity, acceleration, and jerk states from velocity measurements. In addition to this technique, the system requires a sufficiently high measurement and display update rate in order to ensure good aircraft control and the perception of a smooth display by the pilot. Simulator studies performed at MIT suggested an update rate of 6 Hz (i.e., six times per second) or higher for satisfactory control of a typical GA aircraft.

When my advisors and I first introduced this novel approach at MIT, we conducted a number of successful flight tests to proof the viability of pseudo-attitude as a substitute for traditional attitude. In these tests, several pilots flew various maneuvers and approaches using either traditional attitude (i.e., artificial horizon) or pseudo-attitude as their attitude reference, with similar results for both displays.

To meet the need for a high enough measurement and display update rate, the MIT investigators used a high-end GPS receiver providing 10 Hz measurements and a laptop computer serving as a processor and display. The prototype equipment was heavy, and the total cost for the system was comparable to the cost of a typical mechanical attitude indicator.

The Emergence of Handheld Computing

With the emergence of massive computing power in handheld PDAs and more powerful and smaller GPS chipsets in the last few years, it was time to revisit this approach and implement a truly handheld back-up attitude indicator. To that end, I chose a PDA as the computing and display platform. It had a 400MHz microprocessor, 52 Mbytes of usable RAM, and a 320×480 pixel display (though only a 320 × 320 pixel area was used).

For the GPS receiver, I surveyed the market to find one with a minimum update rate of six Hertz for velocity information and cost less than $200. The unit I selected satisfied both criteria. The GPS receiver board cost $150 and, although advertised as having a 4-Hz update rate, it provided 6-Hz velocity data when commanded to do so.

Figure 2 shows the simplified block diagram of the pseudo-attitude system. Pseudo-attitude was displayed in a manner similar to the way that traditional attitude appears on an

Cockpit setup with GPS receiver mounted on dashboard (left) and pseudo-attitude display side-by-side with artificial horizon (above).

artificial horizon. The pseudo-roll representation matched the conventional roll display, but the flight path angle replaced the pitch information.

The software did not occupy more than 23 kilobytes, and the PDA's computing power turned out to be ample. The receiver was mounted to a prototype board containing signal conditioning logic and powered by three AA batteries providing several hours of operational life. The accompanying photo shows the hardware setup.


Handheld attitude indicator consisting of PDA and GPS receiver board.

The Flight Test

To test the system, we chose a clear night last November over the Los Angeles, California, basin. We flew a Cessna C-182RG Skylane aircraft with a 235-HP engine, belonging to Bob Clark, a Los Angeles–based flight instructor who served as test pilot while I operated the system. For this test, we mounted the PDA over the heading indicator using Velcro. This arrangement allowed for a nice side-to-side comparison of both the traditional attitude and the pseudo-attitude indicator. With the Velcro, we could remove the unit quickly, should the need arise.

We secured the GPS receiver to the dashboard with some masking tape. Finally, the antenna was taped to the windshield at its highest point inside the crew cabin. This ensured maximum satellite coverage. The entire setup took just a few minutes. The accompanying photos show the configuration inside the cockpit.

We took off from El Monte Airport during VFR conditions. The GPS position dilution of precision (PDOP) was predicted to increase from 1.7 at the beginning of the test flight to 2.3 at the end of it. The number of satellites predicted to be visible during this time fluctuated between 9 and 10.

We flew over the local practice area and performed some practice maneuvers including shallow and steep turns, climbs, and descents. The pseudo-attitude display followed the traditional attitude display nicely with a slight delay of less than half a second. The latter is expected since the system does not measure the bank angle directly but computes it based on trajectory measurements.

Next, we performed some 60-degree (2-g) turns and a steep climb in rapid succession. Again, the displays matched closely with smooth transitions between the maneuvers. Figure 3 shows pseudo-roll during the steep turns and the flight path angle during the steep climb. Figure 4 shows a side-to-side comparison of pseudo-attitude and traditional attitude using a succession of images captured from the in-flight video. They are 0.16 seconds apart, thus showing each update.

Finally, we embarked on a practice non-precision approach using El Monte's GPS-A approach. The pilot, while not under the hood, referred only to the pseudo-attitude display to obtain attitude information and flew a flawless approach back to the airport. During the post-flight briefing, Bob Clark described the display characteristics as excellent

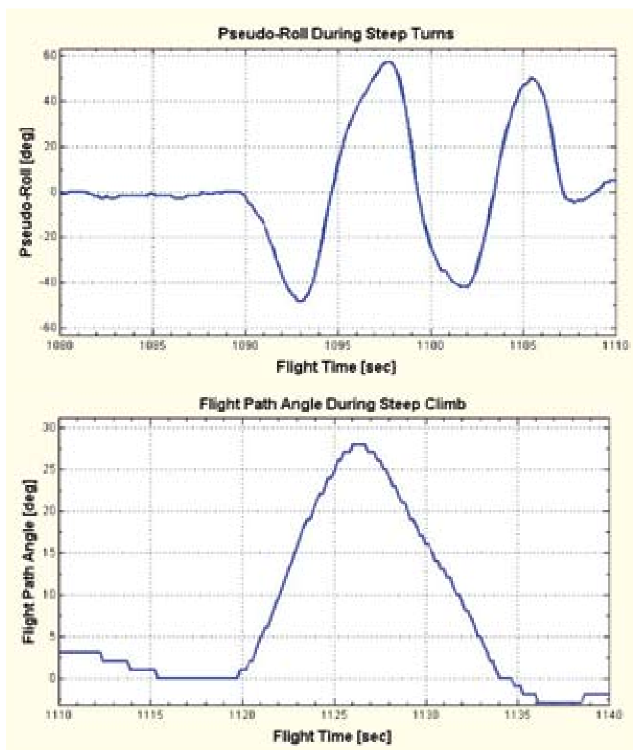


FIGURE 3 Pseudo-roll during steep turns (top) and flight path angle during steep climb (bottom)

FIGURE 4 Side-by-side comparison of pseudo-attitude and traditional attitude captured from the in-flight video. Each image shows the airc

and expressed his satisfaction with the responsiveness of the overall system.

Post-flight analysis revealed a slightly better than predicted PDOP. The number of satellites tracked by the GPS receiver fluctuated between 10 and 12 for most of the test flight, although the number dropped to 6 during one of the 2-g turns without producing noticeable effect. With the antenna mounted high on the windshield, we tracked satellites that were behind the aircraft at high enough elevation as well and thus ended up getting most of the available satellites.

A handheld, integrated navcom transceiver/GPS receiver could now serve as an all-in-one backup cockpit providing communications, navigation, and now aircraft control as well.

Operational Considerations & Conclusions

Although the utility of pseudo-attitude to control the aircraft was demonstrated a few years ago when the MIT team first introduced this approach, the Los Angeles flight test illustrated the possibility of using a PDA and a $150 GPS receiver board to achieve the same goal. Moreover, the hardware was compact, light-weight, and truly portable.

This setup enables a slew of opportunities for handheld devices. For example, handheld GPS moving map devices can also serve as backup attitude indicators displaying pseudo-attitude. Moreover, a handheld, integrated navcom transceiver/GPS receiver could now serve as an *all-in-one* backup cockpit providing *communications, navigation,* and now aircraft *control* as well!

So, what's the catch ?

A number of factors need to be considered to fully exploit pseudo-attitude based systems. First, because the attitude information is based on the assumption of coordinated flight, it will not show proper indications if the aircraft flies unusual maneuvers or is in extraordinary attitudes, such as during a severe slip, stall, or spin.

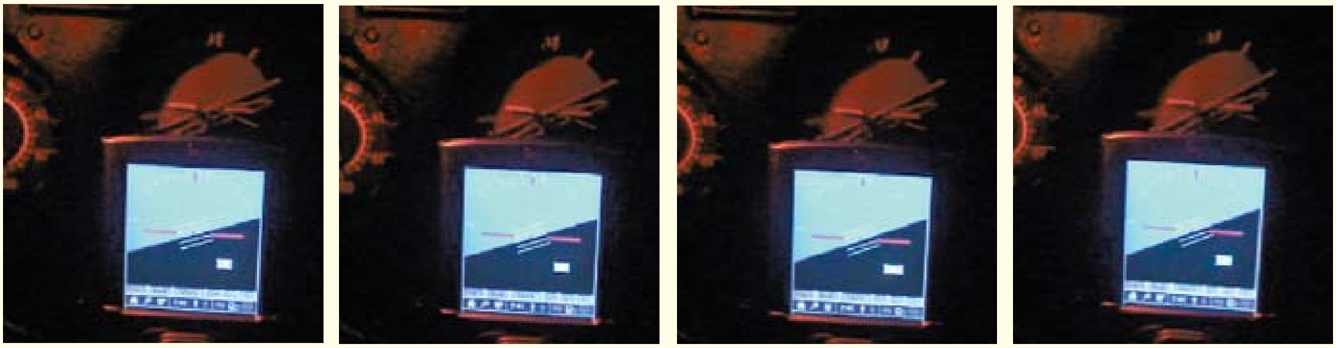
Moreover, during *severe* atmospheric non-uniformities, such as severe gusts, and wind shear, the inertial velocity vector axis and the velocity vector relative to the air may no longer be closely aligned, and in these instances pseudo-roll angle may differ considerably from the aircraft bank angle. (Similarly, it will not show the correct attitude while the aircraft stands still.) When flying coordinated, on the other hand, or even in the presence of moderate sideslip and atmospheric turbulence, proper attitude information is provided even for very steep turn and climb maneuvers.

As outlined before, we recommend a minimum of 6 Hz GPS velocity update rate for good aircraft control and a smooth display. Most of today's handheld GPS receiver market, however, still revolves around chipsets providing 1 Hz position and velocity data intended for navigational awareness only. To display pseudo-attitude effectively, GPS chipsets providing 6 Hz or higher are necessary. The good news is that with today's low power integrated circuits, battery life is not an issue even for faster chipsets.

An additional important consideration is the antenna placement. Careful selection of the antenna location is paramount to good satellite visibility and a smooth attitude display. While an antenna mounted on the outside of the aircraft is the best option, it may defeat some of the appeal of a handheld device. However, a carefully selected spot inside the cockpit, as demonstrated in this flight test, may yield equally good satellite coverage.

Finally, as with all systems relying on GPS, availability and integrity issues have to be addressed. These become even more important if GPS is to be used to provide attitude information in addition to its primary use for navigation, because an erroneous attitude display or the total loss of attitude information may cause the pilot to quickly loose control.

To this end, an effective build-in integrity monitoring system is imperative. Such a system detects if the attitude information is unreliable and informs the pilot of its unavailability. For this flight test, the system monitored the GPS receiver status, the estimated GPS position accuracy, and the



raft attitude indicator (top) and the pseudo-attitude indicator (bottom) at 0.16 seconds intervals.

DOP values to ensure that proper GPS information was available.

The system described in this article is thus best suited as a *supplement* to the existing cockpit instrumentation. Should the primary attitude indicator fail, the GPS based pseudo-attitude system would serve as a backup and reduce pilot workload significantly compared to the traditional needle, ball, and airspeed approach. Still, the latter should ultimately be relied upon in cases of insufficient GPS coverage.

With the antenna mounted at the top of the windscreen (upper left in photo), the GPS pseudo-attitude system (visible on dash) was able to receive signals from almost all satellites visible in the sky.

Acknowledgments

The author would like to thank Bob Clark, a Los Angeles–based instructor pilot, for graciously volunteering his airplane and time to conduct the flight tests for this article, and Leo DiDomenico for providing logistical support throughout the development of the handheld attitude indicator.

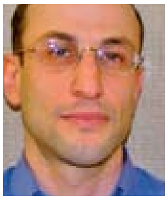
Additional Resources

Kornfeld, R.P., Hansman, R.J., Deyst, J.J., The Impact of GPS Velocity Based Flight Control on Flight Instrumentation Architecture, Report No. ICAT-99-5, MIT International Center for Air Transportation, Cambridge, MA, 1999.

Kornfeld, R.P., Hansman, R.J., Deyst, J.J., "Single Antenna GPS Based Aircraft Attitude Determination," Institute of Navigation, National Technical Meeting 'Navigation 2000', Long Beach, CA; 21-23 Jan. 1998. pp. 345-354. 1998

Kornfeld, R.P., Hansman, R.J., Deyst, J.J., Amonlirdviman, K., and Walker, E.M., "Applications of GPS Velocity Based Attitude Information," AIAA Journal of Guidance, Control and Dynamics, Vol. 24, No. 5, Sept.-Oct. 2001.

Author



Richard Kornfeld is a senior engineer at the NASA/Caltech Jet Propulsion Laboratory (JPL) in Pasadena, California, USA. He holds a Ph.D. in aeronautics and astronautics from the Massachusetts Institute of Technology (MIT) in Cambridge, Massachusetts, and a diploma in electrical engineering from the Swiss Federal Institute of Technology (ETH) in Zurich, Switzerland.

Manfacturers

The PDA used in the most recent version of this pseudo-attitude system is a Palm Tungsten T3 from Palm Inc., Sunnyvale, California, running Palm OS 5.2.1 software, a registered trademark of Palm Trademark Holding Comp. LLC. The GPS technology used to provide position and velocity was an ANTARIS RCB-LJ receiver board containing a TIM-LF GPS module jointly developed by u-blox AG, Thalwil, Switzerland, and Atmel Corporation, Heilbronn, Germany.

The pseudo-attitude technology described in this article is protected by patents. For more information on this technology or its applications, please contact the MIT Technology Licensing Office at 617-253-6966 (Case #7742).

The prototype development of this technique at MIT incorporated a 3151R GPS receiver from NovAtel, Inc., Calgary, Alberta, Canada, as the primary velocity source and a Migits INS/GPS unit from Rockwell Collins, Cedar Rapids, Iowa, as an attitude reference. IG