GPS-Based Attitude and Guidance Displays for General Aviation

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Abstract - **GPS was used with a short baseline (1 and 2 wavelengths) triple antenna configuration to obtain attitude in conjunction with solid state rate gyros. The system was used to provide an inexpensive Attitude-Heading Reference System (AHRS) for use by small General Aviation aircraft. The gyros enabled a high bandwidth output while the GPS was used to estimate the gyro drift rate. The resulting attitude information was used, along with GPS-based position, by a graphical "out-the-window" view with tunnels indicating the desired path in the sky for the current phase of flight. Accuracy and ease of flying are enhanced by the system.**

I. INTRODUCTION

Attitude information for small General Aviation (GA) aircraft is currently obtained by gyros with spinning rotors. A vertical gyro is used for pitch and roll while a separate directional gyro is used for heading. The display of the information to the pilot is presented mechanically by the gyros themselves. Commercial and military aircraft generally have computer-based CRTs or LCD displays (called "glass cockpits") that are driven by inertial reference units (IRUs). These attitude systems cost more than most small GA aircraft. This research is aimed at bringing glass cockpits to GA at an affordable price.

The Global Positioning System (GPS) has been investigated by many researchers for its applicability in determining attitude by differencing signals from multiple antennas [1,2,3,4]. The concept has been used successfully for aircraft attitude in flight [2,3]. These systems, however, require expensive GPS receivers and have not proven acceptably reliable for primary aircraft flight instruments. They utilized a wide separation between antennas (approximately 10m) in order to achieve good accuracy; however, this introduced structural flexibility as an error source thus necessitating an additional antenna for a total of four. The large number of wavelengths (λ = 19 cm so there are 50 wavelengths in 10m) between antennas introduced many possibilities for the integer cycle ambiguity and necessitated aircraft motion or extensive searches to initialize the system. In the use of the system described in [3] over the last 3 years at Stanford University, it has been found that solutions are not reliable and often require extensive taxiing to provide the initialization. If lock is lost in the air, re-initializing takes 10s of seconds. However, when properly initialized, the system was shown to provide attitude to within 0.1 degree.

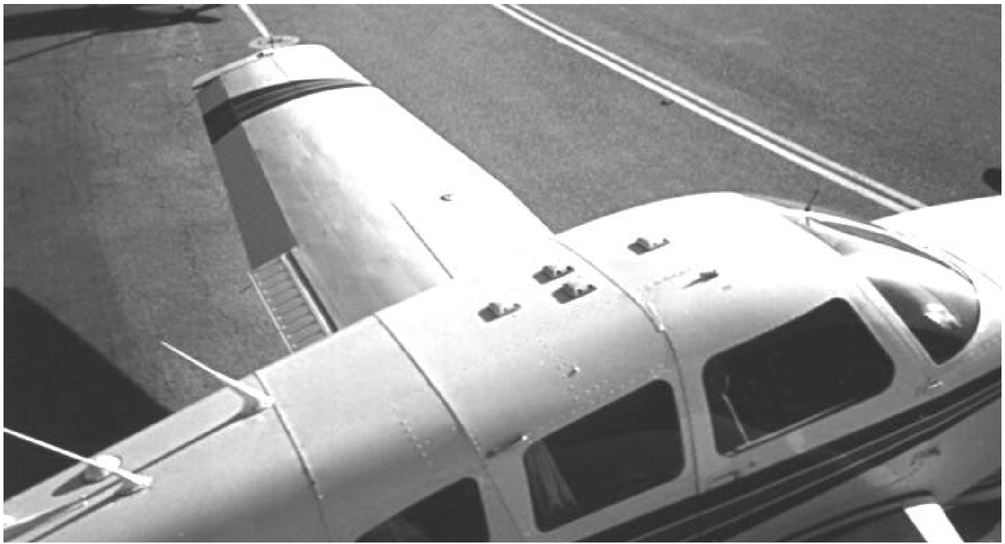

Figure 1. Aircraft closely-spaced antenna array

As part of the goal of this research, we investigated the use of GPS for attitude, but with reduced requirements on the receiver to reduce cost and a more closely-spaced antenna configuration to provide a more robust design for acceptable aircraft use. Although the closer spacing degrades the accuracy of the raw GPS measurements (also reported by [4] for a marine application), our system was enhanced by adding inexpensive solid-state rate gyros to smooth the noise and to provide a high bandwidth response even when using the less expensive GPS receivers with 1 Hz sampling.

II. GPS-GYRO AHRS SYSTEM DESCRIPTION

A. *Test Aircraft*

A Piper Dakota was used as the test bed for all the GPS attitude and display testing. Three active GPS antennas were permanently mounted on the fuselage as shown by the forward 3 antennas in Figure 1. The fourth antenna shown at the aft part of the constellation was used for other purposes.

B. *GPS Receiver*

The receiver used was a Trimble Quadrex. Its architecture is described in [3] in detail, however, it basically multiplexes between the different antenna inputs and is capable of a 10 Hz sample rate. Although it is not representative of a low-cost receiver, it is currently being used to verify the algorithms and gyro smoothing aspects of the system. Our partner in the overall effort, Seagull Technology, Inc., is developing the low cost 1 Hz receiver. The 3 antenna channels used were each able to track 6 satellite channels with an accuracy of approximately 0.5 cm. No clock errors existed between the satellite channels because all were controlled by the same clock. Figure 2 shows a schematic diagram of the receiver.

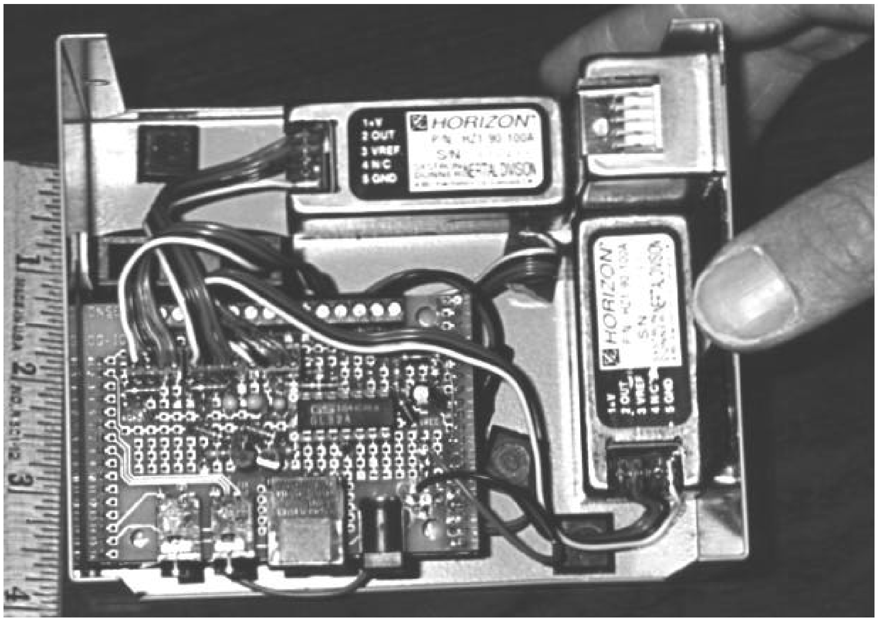

Figure 3 .Gyro array installation

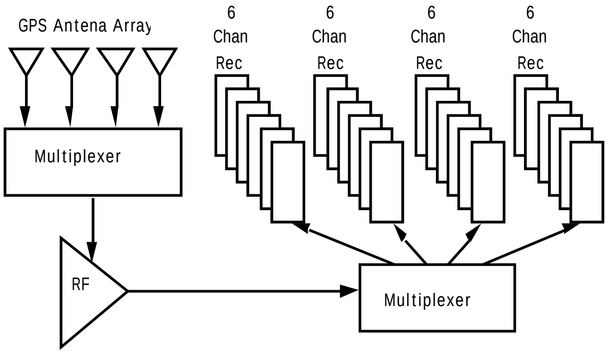

Figure 2. Receiver schematic diagram

C. *Gyros*

Three Systron-Donner Horizon gyros were placed orthogonal to one another. This is shown in the upper right hand corner of Figure 3. These were designed to be high-production automotive grade and the prices are projected to be significantly lower than previous aircraft quality gyros. In quantities of 10, these units currently are priced at $600 each. The short term drift stability is reported to be .045°/sec for this gyro by the manufacturer.

D. *Attitude Algorithm*

The attitude algorithm is described in [5]. It solves for the 3 components of each baseline vector (the vector from one antenna to another) and the clock error/line biases. The determination of the integer ambiguities at initialization was performed extremely fast due to the fact that one antenna pair (rear two) was 19 cm apart and the other pairs were 36 cm apart. The typical integer search took approximately 0.5 sec, partially because it was aided initially by the fact that the airplane is near level at system start on the ground, but mostly because there were so few possible values of the integers due to the antennas being less than one or two wavelengths apart. In the air, the gyros would provide a good attitude estimate for re-initialization; however, this was only rarely required.

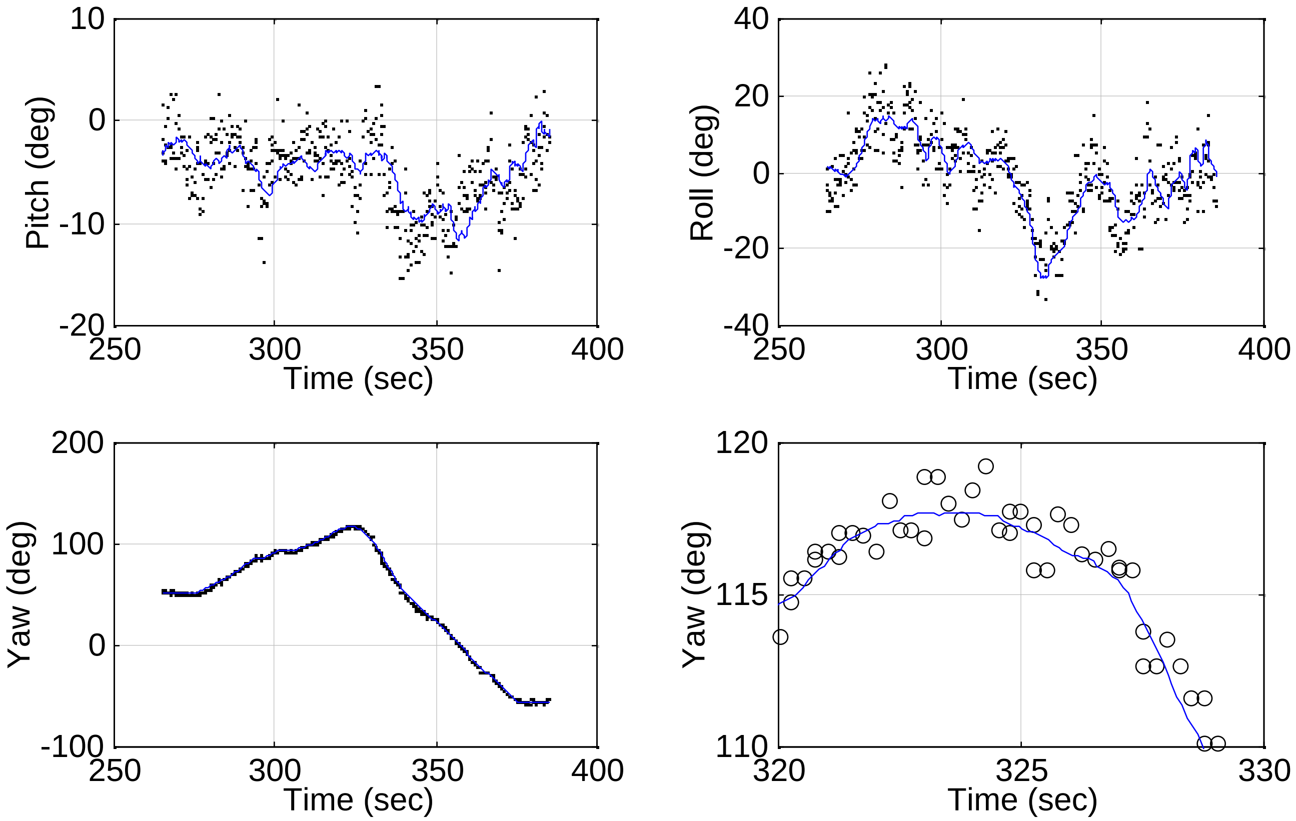

Figure 4. Flight Test Results

E. *Gyro-GPS Integration Algorithm*

The algorithm for smoothing the GPS attitude solution in real-time sampled the output from the three gyros at a fast rate (10 Hz nominal). The output from the gyros was numerically integrated to provide an estimate (time update) of the three Euler angles. This information was subsequently sent to the display at the same rate. The GPS receiver output was sampled at a slower rate (4 Hz nominal). A Kalman Filter was used to integrate the GPS attitude solution with the estimates obtained by straight integration of the gyros. The GPS measurements also provided a means for estimating the gyro drift rate.

The filtering and integration algorithms were performed using a TattleTale Model 8 (Shown in the lower left of Figure 3.) by Onset Computer. The TattleTale Model 8 consists of a Motorola 68332 Processor with 8 12 bit A to D lines and 16 Digital I/O lines. The algorithms were written in C and compiled using an Aztec C Compiler.

F. *Gyro-GPS Integration Results*

Figure 4 shows the output of the integrated Gyro/GPS attitude system. As can be seen, considerable smoothing of the raw GPS attitude solution (shown as dots and circles) is obtained by the integrated gyro-GPS system (shown as a solid line). A comparison of the raw GPS attitude solution also shows no lag in the gyro smoothed attitude solution displayed. Furthermore, during a series of flight tests two of the authors flew the Piper Dakota test aircraft using the attitude information displayed by this system. They had no difficulty controlling the aircraft using only the attitude information generated by the integrated GPS and gyro system.

III. DISPLAY SYSTEM DESCRIPTION

A. *Introduction*

The attitude algorithms previously described make it possible to take full advantage of differential GPS by presenting the pilot of a light aircraft with a three-dimensional (3-D) picture of the "out-the-window" view. Such a display intuitively depicts the desired flight path and runway environment even in instrument flight conditions. A prototype display was developed and tested in piloted simulations and in flight, demonstrating some significant benefits over conventional displays.

The loosely-integrated set of dials, gauges, and indicators in today's light aircraft is difficult to use in instrument flight conditions. A good example is the Instrument Landing System (ILS) receiver and display, the most accurate landing system normally used in light aircraft [6]. The ILS display consists of two needles that indicate lateral and vertical angular deviations from the straight-in approach path. A significant amount of training and skill is required to smoothly fly an ILS approach by hand. Because the missed approach leads the aircraft away from the straight-in approach path, the ILS is of no use during this procedure. These characteristics all contribute to a more fundamental problem: that it is easy to lose situational awareness when using an ILS needle indicator.

To enhance situational awareness, researchers have been working for some time on displays that integrate the many data sources needed for flight with a 3-D perspective view of the outside world. The desired flight path is presented as a tunnel or series of symbols for the aircraft to fly through and has been called a “highway-in-the-sky”, “pathway-in-the-sky”, or “tunnel” [7-9]. Most of the work on 3-D perspective displays has centered on laboratory simulation or heavily-instrumented flight test aircraft [8, 10]. Our goal was to demonstrate the practical application of enabling technologies to a system that addresses the operational, budget, power, and form-factor constraints of light aircraft.

B. System Description

Differential GPS (DGPS) was used to provide positioning data to the display. It was a mini version of the FAA's Wide Area Augmentation System (WAAS) [11,12] that is scheduled to become available to all aircraft in 1998. It provides 2 m 95% vertical accuracy, enabling scenes reconstructed from a 3-D database to very closely match the actual view out the cockpit window. GPS attitude augmented with rate gyros was also a critical component of the 3-D perspective display system, since a data latency less than 100 msec was needed to create a smooth picture with no perceptible lag.

The 3-D scene was presented on a 320x234 pixel 5.5 inch diagonal active-matrix liquid crystal display (AMLCD) attached to the instrument panel glareshield. Availability of reasonably-priced flat panel displays has traditionally been a barrier to putting computer displays in light aircraft. Fortunately, the growing popularity of laptop computers is now rapidly bringing down the price of AMLCDs and has enabled the first generation of cockpit computer systems with sunlight-readable displays. The display was driven by a ruggedized 90 MHz Pentium personal computer with a 64-bit graphics accelerator card.

The tunnel display, shown in Figure 5, was kept simple to minimize computational requirements and enhance ease of use. The field of view represented was 40 degrees vertical by 50 degrees horizontal and included the runway and control tower depicted in correct perspective. The approach and missed approach paths were depicted as "hoops" 100m wide with a spacing of 500m on straight segments. On curving segments the spacing was reduced to 200m to allow the pilot to better see the tunnel, which curved out the side of the display when the aircraft was in a turn. The 3-D scene could be replaced by a full-screen ILS needle display for comparative testing.

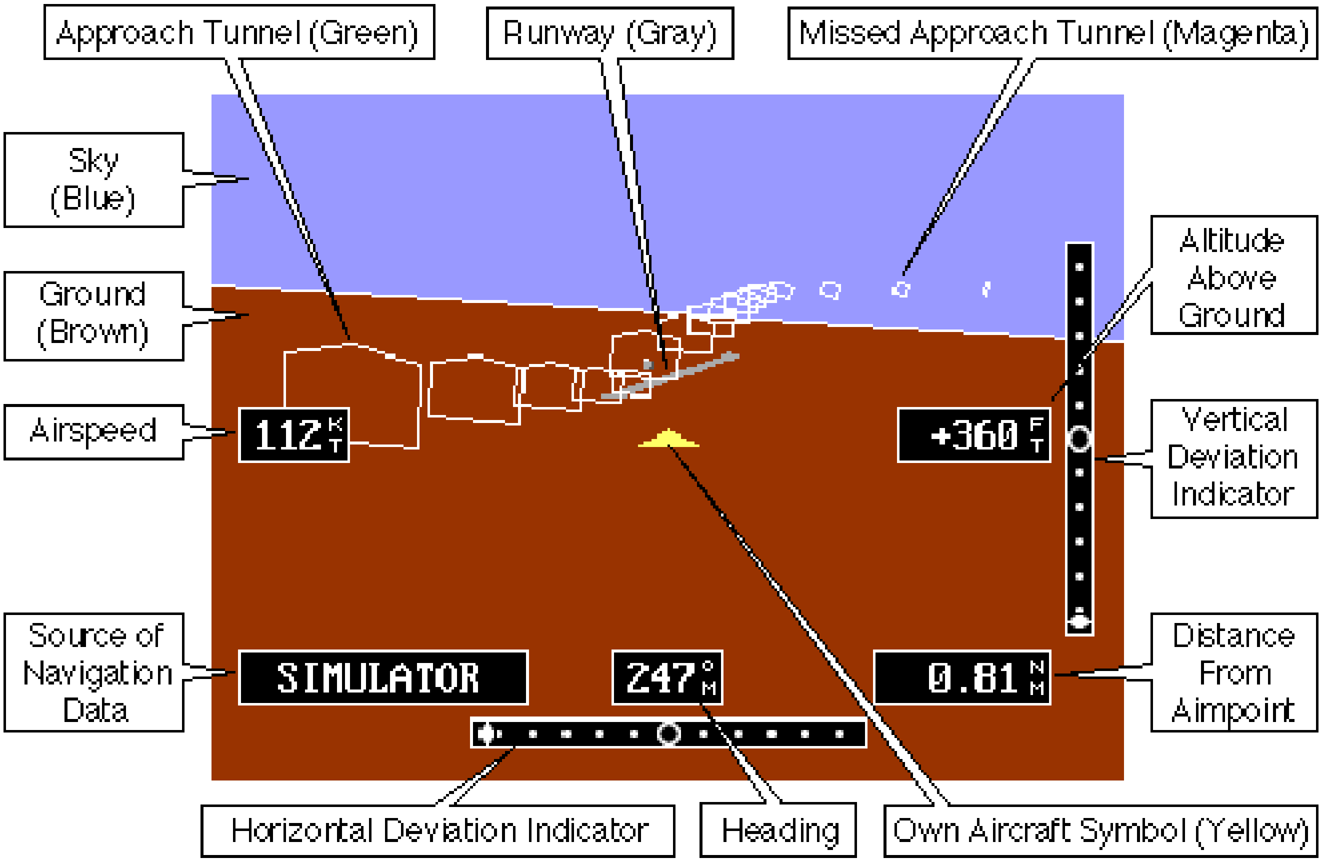

Figure 5. Tunnel Display

C. Display Testing

The display was tested in flight on the Piper Dakota and on the ground using a high-quality personal IFR procedures simulator. The pilot flew using the tunnel display and with the ILS needle display for comparison. The flight paths included an intercept of the final approach course, a straight-in final approach, and a curving missed approach with a climbing right turn. Results discussed here are based on twelve simulator approaches and four actual approaches to runway 25R at Livermore, CA. Flight tests included a safety pilot while primary pilot reference to the glidepath was the GPS-based display with both the tunnel and ILS needle formats used. For the simulator runs several wind directions were used, varying from a crosswind to straight down the runway.

The tunnel display approaches showed generally smaller path following error than the ILS needle display runs. In simulator tests, root-mean-square (RMS) vertical FTE for the tunnel display was 14.2 m compared to 27.5 m for the ILS needle display. In flight, the vertical RMS FTE had the same order of magnitude for both displays (13.2 m for the tunnel display; 19.4 m for the ILS needle display). One of the ILS needle runs exhibited a vertical deviation of more than 50 m above the glideslope.

More importantly, final approach intercepts for both simulated and actual runs showed that the pilot had less tendency toward overshoot and undershoot using the tunnel display. After intercept, additional hunting for the lateral path was evident when using the ILS display. The tunnel runs show that the pilot achieved smoother lateral intercepts when confronted with varying wind conditions. One of the inflight ILS needle runs exhibited an overshoot of the runway centerline of almost 0.5 km.

A bird's eye view of all twelve simulator approaches is shown in Figure 6. On such a large scale, lateral deviations on the approach are difficult to see; however, the missed approach segments look quite different. The curving missed approaches using the tunnel display collapse onto one thick trace, showing that the pilot was able to repeat the curving flight path with each of the varying wind conditions. The missed approaches flown using conventional techniques show scatter due to different wind conditions and differing initiation points. Since the pilot consistently ended the right turn at a predetermined heading, the varying winds caused different ground tracks for each run. This illustrates the reason for setting aside large obstacle clearance areas when setting up conventional missed approach procedures [13].

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Figure 6. Simulator Ground Tracks

D. Display Test Results

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

1. Piloted simulation indicated that the tunnel display could improve FTE over that provided by an ILS needle display on a straight-in approach, while limited flight data suggested that path-following error characteristics were similar for the two displays.

2. The pilot reported that perception and control was most difficult in the vertical dimension, a result which agrees with [8]. Enhanced depiction of vertical error is necessary to give the pilot better vertical control.

3. Experiments showed that lateral and vertical flight path intercepts could be executed more smoothly with the tunnel display than with the ILS needle display.

4. In piloted simulation, the tunnel display allowed repeatable ground tracks on the curving missed approach, even in the presence of varying wind conditions.

5. Large flight path deviations were more easily recognized with the tunnel display, allowing the pilot to make corrections sooner.

In summary, the natural 3-D display format allowed intuitive recognition of the aircraft's relation to the desired flight path. This demonstrates that a GPS-based tunnel display can make flying along straight and curving flight paths in light aircraft easier and safer. This will be essential in future air traffic environments and is expected to pay additional benefits in specialized applications such as aerial fire fighting, agriculture, search and rescue, military operations, flight test, photogrammetry, and medical evacuation.

IV. INTEGRATED AHRS DISPLAY SYSTEM

The integrated system (Figure 7) is essentially the inexpensive gyro-GPS AHRS system described in Section II, and DGPS providing velocity and position information. This A/C state information is then passed to the "out-the-window" display allowing an accurate picture of the VFR world to be painted even under IFR conditions.

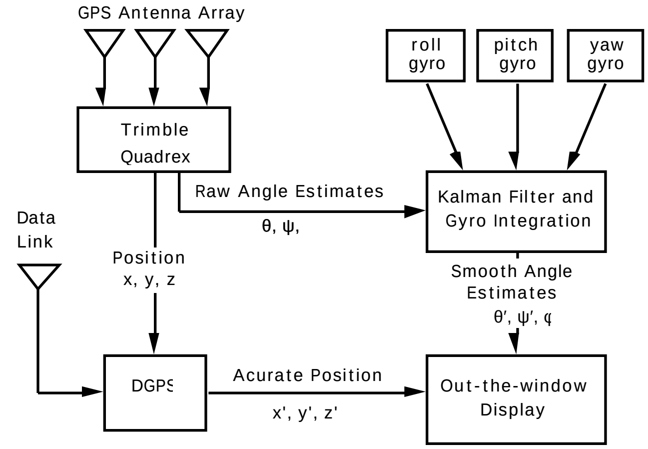

Figure 7. Integrated System

IV. CONCLUSIONS

The combination of accurate, low cost position, velocity, and attitude information with advanced cockpit display technology allows for a real time display system significantly better than existing GA systems. The integration of all of these technologies is what sets this system apart from current display systems. Without any one piece of the integrated system the drastically improved display would not be possible.

V. ACKNOWLEDGMENTS

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