

# Behind The Glass

By Greg Richter

## ***Glass Houses***

The all glass cockpit that was once the wave of the future is finally becoming commonplace. I've personally flown in dozens of them from RVs to L-39s to helicopters and one-off designs, and their builders all have the same questions: How does the solid-state attitude system work? How much can I trust it? What can go wrong? The Attitude Heading Reference System or AHRS that's the core of a glass cockpit EFIS is also the center of most of the confusion. We'll take a look here at how an AHRS works, what it does, what it doesn't do so well, and how to flight test one.

## ***All Electronic***

An AHRS (usually pronounced Ay-Hars) is a collection of electronic sensors that can detect both acceleration and rotational rates with an onboard processor to compute the pitch, roll and yaw of the box. You will sometimes hear the term IMU, for Inertial Measurement Unit, which is a device that provides the raw sensor data. An IMU and a computer to do the math make an AHRS. Add a display to it, and you've got an Attitude Display Instrument, or Electronic ADI. You'll also sometimes here the term INS, for Inertial Navigation System, which is an AHRS good enough to give accurate position and velocities as well as Pitch, Roll and Yaw. They are not commonly used in light aircraft because of cost, although there are some out there. Now that we've got the new words down, let's take a look at how they work.

## ***Delta Theta***

If the inertial community had a fraternity it'd be called Delta Theta, since at the core of any AHRS or INS is a collection of circuitry that measures angle changes using rate sensors. Rate sensors come in several flavors from Ring Laser Gyros (RLGs) and Fiber Optic Gyros (FOGs) to the lowly MEMS sensor that we use in our airplanes.

MEMS stands for micro electromechanical system, and MEMS sensors are micro-machined vibrating silicon forks that look and act a little like tuning forks. If you hold a vibrating tuning fork vertically in your hand and move it away from you, it will twist slightly in your fingers due to Coriolis effect. A vibrating fork inside a MEMS sensor similarly detects motion about its active axis and reports these rate changes as a voltage. If you take a trio of these rate sensing gyros (gyro is the traditional term, even for a silicon rate sensor!) and arrange them one for Pitch, one for Roll and one for Yaw, you're halfway home.

Given three axes of rate sensing, it would seem a simple matter of adding up the measured rates in degrees per second over a known number of seconds to arrive at *how much* we've moved and hence the new angles of Pitch, Roll and Yaw. It's like making a procedure turn – 3 degrees per second for 60 seconds and we'll 180 out of here, right?

So, take a trio of sensors and a microprocessor to add up the small changes that integrate up to motion and there you go – instant AHRS. It'll actually work but, as usual in engineering, there's a bit more to do before we cut metal and start soldering.

### ***Time and Temperature***

A usable, single axis MEMS sensor costs from fifty bucks to several thousand depending on performance. That's a real bargain compared to FOGs at a thousand bucks and up and ring lasers at breathtaking, DOD-level prices.

The good news, then, is that MEMS sensors are cheap, the bad news is that a MEMS sensor sitting on the bench reports motion that isn't there, drifting around like a student on his first cross country. This movement around zero is called *bias drift* and bias compensation schemes and erection logic are guarded by most companies as the proprietary magic they are, although the basics are straightforward.

Most methods of bias compensation utilize ground testing to characterize how each sensor behaves with time, temperature and acceleration. These curves result in a starting point that can improve the base bias drift of a sensor by a factor of 10 or more. Given that even *after* calibration commercial MEMS sensors still wander about 20 to 200 degrees per hour, they still need some help to be useful to a pilot.

Here's why:

A gyro that drifts 120 degrees / hour will drift 2 degrees per minute. After a two-minute procedure turn, that gyro will be off 4 degrees. Remember we had three sensors? You could be 4 degrees or so wrong in pitch, roll and yaw, which is not very helpful. Some of the more primitive electronic ADIs can be off as much as 5 degrees after a procedure turn, and this is where the error comes from.

### ***Aiding With Accelerometers***

To help solve the drift problem our trio of rate sensors is typically aided by a trio of accelerometers that can detect the angle that the airplane makes with the earth. Correcting drifting gyros with accelerometers is known as Erection -- named from scheme used in mechanical gyros where an air blast would stand the gyro card up in the window.

A common single axis accelerometer, like a carpenter's level, measures the acceleration of Gravity with varying angle and works fine on the ground, but not in the air while turning. The problem is that in a coordinated turn the acceleration vector is down through the floor and our level shows we are level even though we are banked and turning. A simple approach is to read the accels when the airplane is *not* turning to correct for gyro drift and to rely on the gyros alone when the airplane *is* turning. This approach is called *Cutout*, and the software that determines when to use which sensor is *Cutout Logic*.

This shows why bench testing an AHRS tells you exactly nothing. A carpenter's level (or your inner ear) does a great job on a tabletop, but can't be trusted to show bank angle in a coordinated turn. Simple AHRS designs get into trouble when you fly in the region where the cutout logic can't decide to use their accels, their gyros or both. More sophisticated designs use techniques like Kalman filtering and adaptive estimation to make better decisions about which sensors to use when and to what degree in the solution.

## ***Velocity Aiding***

Most missiles and guided bomb packages take accelerometer aiding a step further and do *velocity aiding* as well. Since the AHRS or INS also knows velocities in three dimensions, a stable velocity estimate from a VOR, TACAN, GPS or Doppler Radar receiver can be used to refine the solution provided by the gyros and accels. Blue mountain, Garmin and Systron-Donner all provide GPS aided packages, as do other weapons-grade suppliers. If an AHRS flies well unaided, GPS or Doppler can only make it better.

A common question is if GPS or Doppler velocities work, why not use airspeed and save the cost of the radio? While generating acceptable estimates in most cases, airspeed aiding can generate substantial errors when turning into or away from the wind and when the wind is an appreciable fraction of the aircraft's speed -- like in a helicopter, or an airplane turning base to final. Airspeed is the same as aircraft body motion with no wind and when perfectly coordinated, so this approach works well some of the time, but not reliably all the time.

Another less common but eminently practical approach is to use magnetic information from a flux gate or magnetometer. At high altitudes where magnetic anomalies aren't a factor, and at middling latitudes, this can work very well. Many commercial designs use some form of magnetic aiding.

AHRS solutions that can provide a flyable solution without outside aiding of any kind are called *autonomous* and are the highest-grade instruments available. When testing an AHRS or INS it's important to evaluate both its aided and its autonomous performance, and how well it switches between these modes.

## ***Flight Test***

A good vacuum or electric horizon should be able to make a complete 360 turn at standard rate and not be off by more than 3 degrees. Not very impressive, but that's the spec! A good electronic instrument should do significantly better. Here's what to look for when flying any electronic attitude instrument:

All of the below tests should be conducted with the equipment installed as recommended by the manufacturer, and then again with no Pitot, Static, GPS or Magnetic sensors connected. The first test will give you best-case performance when everything is working, the second will show you what you can expect when the GPS antenna fails or your Pitot tube freezes and you have to go autonomous.

Take a safety pilot with you, a pad and pencil and pick a nice VFR day. Remember to do clearing turns and keep an eye out for traffic and the ground!

### **Taxi and Takeoff Roll**

Line up on the runway and hold. Set the ADI level, and takeoff normally. During the takeoff roll the ADI should show level with no errors in pitch greater than two degrees. Watch closely and match the ADI with the visual horizon during rotation and climbout.

### **Slip / Skid**

Once at altitude, uses the rudders all the way left and right for Dutch Rolls. Then hold the Rudder down for ten (10) seconds and skid the airplane watching the ADI to make sure it stays level.

### **Chandelle**

From altitude, dive to V<sub>no</sub> (or as fast as you can go safely) and pull up and turn 180 degrees bleeding off airspeed quickly. During this test, you are turning and decelerating continuously throughout the maneuver, which will show you what to expect from an unusual attitude recovery. Watch the visual horizon on the first run, and then try to recover on the instrument on the second. Your safety pilot should tell you to break off if the instrument gets too far away from a flyable solution.

### **Slow Flight**

This is an easy one, and very useful to see what kind of performance you'll get on the ILS. Pick a day with the wind at 10 knots or more at altitude. Fly a simulated traffic pattern at altitude and approach to landing as if you were going to practice power off stalls. Fly minimum controllable airspeed turning into the wind from all four directions at varying bank angles. This will give you an idea of what the machine will do at low speed in an Approach that becomes a Go Around.

### **Descending Spiral**

Pilots don't like this maneuver because it's the one we bought a gyro to keep us out of -- the classic VFR into IMC spiral.

From altitude, pick a point on the horizon and roll into a gentle turn of five degrees bank and increase bank angle each time you pass that point. Bank 5, 10, 20, 30, 45 and 60 while descending and picking up speed. Recover to level on the instrument only as in the Chandelle above. The idea is to make sure you can follow the gyro if the horizon is obscured. You should be able to recover from an unusual attitude *on the instrument*.

There's a bunch more that you can do in flight test, but this will give you an idea of the performance of your new electronic instrument and what it does and doesn't do. The most important thing to do is to repeat the above tests without airspeed, magnetic or GPS

connected to see what the autonomous performance of your unit is. This will show you what you can depend on when the chips are down and you *need* the instrument to save your bacon. If the device can be used to recover from an unusual attitude without external aiding, it's doing the same job as a gyro and is a suitable replacement for one. If not it's less than useless – it's dangerous.

### **More?**

There is, of course, rather a lot more to building a commercial or weapons grade AHRS than we can cover in one article. If you want to dig in and learn more about how these systems work and what the next generation of AHRS / INS equipment looks like, check out these websites:

<http://bluemountainavionics.com>  
<http://xbow.com>  
<http://honeywell.com>  
<http://www.baesystems-gyro.com>  
<http://www.systron.com/>

EFIS, AHRS and INS systems  
AHRS and IMU systems  
AHRS, IMU and sensors  
MEMS Sensors  
MEMS Sensors

### **Access**

Greg Richter is President of blue mountain avionics and flies his homebuilt (now factory-made) INS in his CozyJet. [greg@bluemountainavionics.com](mailto:greg@bluemountainavionics.com)